

Consistent Concepts of Self-organization and Self-assembly

We critically review concepts of self-organization and self-assembly, and extract from this analysis consistent and workable definitions of both concepts that are applicable across many scientific disciplines. In essence, we distinguish self-organization from self-assembly on a thermodynamic basis, where self-organization implies a nonequilibrium process and self-assembly is reserved for spontaneous processes tending toward equilibrium. This discrimination is consistent with early uses of both terms. © 2008 Wiley Periodicals, Inc. Complexity 14: 10–17, 2008

**JULIANNE D. HALLEY AND
DAVID A. WINKLER**

*Julianne D. Halley and David A. Winkler are affiliated with CSIRO Molecular and Health Technologies, Private Bag 10, Clayton South MDC 3169, Australia.
(e-mail: dave.winkler@ccsiro.au)*

River networks, oceans, and the atmosphere are all examples of systems that form structure and order in the physical world [1]. However, at least two fundamentally different types of decentralized pattern formation mechanism are responsible for this organization. Self-organization and self-assembly both describe processes that give rise to collective order from dynamic small-scale interactions. However, several early and important references suggest that there are fundamental differences between these types of mechanism. Despite these differences, the terms are now often used interchangeably, and each scientific discipline tends to have its own way of describing the concepts [2]. Given increased interest in complex systems science and hope that universal features of complexity might one day be identified, clear and simple characterization of these concepts is essential for efficient communication across disciplines. Otherwise, attempts to illuminate the full importance of self-organization in physical and biological systems will be unnecessarily obscured.

Consequently, we report a critical review of common definitions of self-organization and self-assembly from the broad literature, extraction of their common, robust, and discipline-spanning elements, and the use of these elements to form consistent and workable definitions that are applicable across most, if not all sciences. In essence, we distinguish the two processes on a thermodynamic basis. Although self-organization implies a nonequilibrium process, self-assembly is reserved for spontaneous processes tending toward equilibrium. This distinction is consistent with early uses of both terms [3–6]. To clarify our definitions, we discuss examples of both processes. We also highlight the complex nature of the boundary between these processes with other carefully chosen examples. Our

analysis reveals that there are some systems that are difficult to classify as either process, and others that have the characteristics of both.

SELF-ORGANIZATION

Despite some instances where certain equilibrium systems have traditionally been labeled self-organized (e.g., crystallization, alignment of magnetic domains [7]), most agree that self-organization requires an external energy source and is therefore dissipative [3, 8–14]. This requirement is consistent with the second law of thermodynamics, which prohibits spontaneous ordering in closed equilibrium systems. Nonlinearity is also thought to be an essential requirement for self-organization, although by itself is clearly inadequate [9, 12, 15]. The dissipative nature of self-organized structures means that once energy input ceases, the self-organized order invariably decays [10].

We stress the requirement of nonequilibrium conditions for self-organization, because this is the primary feature that distinguishes the concept from self-assembly. This requirement therefore needs to be made explicit in definitions of self-organization to avoid confusion. Following [3] and [16], several authors [17, 18] defined self-organization as a set of dynamical mechanisms whereby structures appear at a global system level as a result of interactions between its lower level components. Although the phrase “dynamical mechanisms” suggests nonequilibrium, it is not sufficiently specific because mechanisms of self-assembly are also dynamic (*vide infra*). Without explicit mention of the dependence of order upon nonequilibrium conditions, definitions like those mentioned earlier fail to distinguish between mechanisms of self-assembly and those of self-organization.

Similarly, a recent review by Camazine et al. [19] of self-organization defined it as a process in which patterns at the global level of a system

emerge solely from numerous interactions among lower-level components. The rules specifying these interactions are executed using only local information, without reference to any global patterns [19]. This definition also fails to distinguish self-organization from self-assembly, as self-assembly is also characterized by numerous interactions among lower level components in the absence of global information. Moreover, the definition relies on other ill-defined terms such as “emerge” and “local” versus “global” information, and these terms may be more difficult to define than self-organization [20]. An additional problem with this [19], definition is the requirement that pattern emerges solely from interactions among lower-level system components. In our view, this requirement is misleading because self-organizing systems are thermodynamically open and invariably immersed in their environments. Consequently, the self-organizing order necessarily reflects both order from interacting components and order that preexists in local environments. In our view, the intimate dependence of self-organizing systems on their environment is too often overlooked. For example, the order that characterizes convection cells is typically described as a consequence of numerous small scale interactions among molecules, with little regard for the templates provided by the direction of heat and gravity. In many cases, a strict separation between the physical and social environment may not be possible, as they may be interdependent [21]. Indeed, it may be unrealistic to assume a sharp boundary between structures emerging from “pure” self-organization and cases representing mixtures between self-organization and contributing templates [19, 22, 23].

We argue that self-organization necessarily reflects an interplay between internal and external sources of order. Of course, to be self-organized external sources of order must not be the pri-

mary ordering force, but merely a constraint that provides context in which internal ordering mechanisms play out. The definition of Camazine et al. is not the only one that overlooks the importance of local environments of self-organized systems. It is often stated that self-organization occurs through multiple interactions in the absence of centralized control or other guiding template [23]. We consider all types of external sources of order as templates. It follows that because all self-organized systems are thermodynamically open and immersed in local environments, all self-organizing systems are constrained in some way by external templates. Camazine et al.’s, statement that a template is a “full-size guide or mold” is not correct as Anderson [24] points out.

Self-organization transcends most (if not all) scientific boundaries. Hence, an appropriate definition of self-organization must also span such boundaries. Many definitions in the literature are limited because of inclusion of terms or concepts that are wedded to specific fields. For example, De Wolf and Holvoet consider self-organization a dynamical and adaptive process where systems acquire and maintain structure themselves, without external control. Structure can be a spatial, temporal, or functional structure [25]. We caution against using definitions of self-organization that involve adaptation, as this has meaning only in a goal-oriented or biological context. For example, should convection cells be considered adaptive? A second problem with this definition concerns the requirement that there be no external control, that is, the absence of direction, manipulation, interference, pressures, or involvement from the environment. Again, the nonequilibrium nature of self-organized systems means that they necessarily have this involvement to some extent.

A similar limitation exists in Collier and Taylor’s definition [20]. They focus

on engineered systems and provide a technical definition of a self-organizing system, as “one where a collection of units coordinate with each other to form a system that adapts to achieve a goal more efficiently.” Although such a definition clearly yields some good in the narrow context of self-configuring wireless sensor networks, it does not elucidate the term self-organization in biological contexts, where it tends to evoke a slight sense of mystery [26]. The association between goal-oriented behavior and self-organization is misleading, because in biology some examples of self-organization are epiphenomena that have no goals, while others are neutral or detrimental [27, 28]. In addition, the use of the term “coordination” is misleading, because in social insect colonies (and many other complex systems), apparent global coordination can arise through conflict, antagonistic interactions and inefficiency. Such order is not true coordination because it is due, at least in part, to a competitive rather than cooperative process. Those autocatalytic loops that are most strongly reinforced are selected naturally, while others collapse. The similarity between interactions of feedback loops in self-organized systems and those giving rise to natural selection is striking and is discussed elsewhere [29].

Gershenson and Heylighen [30] suggested that a definition of self-organization first requires a definition of “self” and “organization.” This led them to consider the role of an observer, culminating in the conclusion that self-organization is a way of observing systems, and not a phenomenon in its own right. We argue that a definition of self-organization need not depend on definitions of self and organization because the property of self-organization is not reducible to such terms. We will provide a definition that it stands alone and independent of other complex terms.

Arguably, the best description of self-organization is one provided by Coveney and Highfield in their gloss-

sary: self-organization is the “spontaneous emergence of nonequilibrium structural organization on a macroscopic level due to collective interactions between a larger number of simple (usually microscopic) objects” [11]. However, this definition also suffers from the problem of defining “emergence.” Moreover, the definition fails to recognize the importance of local environments and external templates that invariably interact with any self-organizing order.

Many authors avoid the problem of defining self-organization by instead listing its key components. However, even these vary considerably among authors and scientific disciplines [3, 18, 19, 23, 31–35]. We therefore suggest a new classification scheme that divides prominent features of self-organization into either primary or secondary classes, according to their fundamental nature. Primary elements are those that cannot be derived from other elements, while secondary elements are those that are derived from primary elements. The primary ingredients of self-organization are (1) positive feedback, (2) negative feedback, and (3) interactions among multiple system parts. The latter element may be somewhat redundant as feedback necessarily implies interaction. Another feature often listed as a key ingredient of self-organization is randomness, which facilitates the discovery of new solutions [19, 36]. We chose not to list randomness as a primary feature of self-organization for three reasons. First, the actual mechanism that enables randomness to influence self-organization is feedback. Second, self-organized systems can function in chaotic environments, in the complete absence of randomness. Third, there may not be such a phenomena as true randomness [37]. The primary features of self-organization produce at least three secondary features: (1) amplification of fluctuations, (2) bifurcation, and (3) multistability. These signatures of self-organization have

been discussed in detail elsewhere [3, 19, 31, 38].

In the light of aforementioned criticisms, we define self-organization as follows.

Self-organization is a dissipative nonequilibrium order at macroscopic levels, because of collective, nonlinear interactions between multiple microscopic components. This order is induced by interplay between intrinsic and extrinsic factors, and decays upon removal of the energy source. In this context, microscopic and macroscopic are relative.

SELF-ASSEMBLY, AND HOW IT DIFFERS FROM SELF-ORGANIZATION

Unfortunately, the term “self-assembly” has been overused to the point of cliché [39] and is sometimes used interchangeably with the term self-organization and other words and phrases of imprecise or multiple meaning [2]. The use of the concept of self-assembly is increasing in many disciplines, with a different flavor and emphasis in each [2]. In chemistry, self-assembly is typically associated with energy minimization processes and thermodynamic equilibrium [40–42]. Whitesides and Grzybowski [39] divide self-assembly into two categories: static and dynamic. Static self-assembly corresponds to what most chemists would recognize as molecular self-assembly, while dynamic self-assembly corresponds to what biologists understand as self-organization, although Whitesides and Grzybowski do not use this term. In polymer chemistry, Yamaguchi et al. [43] consider self-assembly and dissipative structures as equilibrium, and nonequilibrium forms of pattern formation, regarding them as two complementary manifestations of self-organization.

In the social insect literature, self-organization and self-assembly appear to be conceptually indistinct [23]. This ambiguity is partly due to Sendova-Franks and Franks who reinforced

Miller's early, but limited definition of self-assembly as an assembly process in which only the constituents of the final structure take part [44, 45]. This definition is problematic because it means that the majority of examples of self-assembly (across multiple levels of biological organization) will also be examples of self-organization [45]. For example, assemblages of workers that grip onto each other to form curtains, bivouacs, bridges, and other complex collective structures are considered self-assemblages, because only the constituents of the final structure take part [23, 45, 46]. This definition is further complicated by adoption of the term self-assembly to describe qualitative stigmergy (*vide infra*). If self-assembly is a process in which only constituents of the final structure take part, qualitative stigmergy cannot be considered self-assembly because individual animals are not part of the final structure. Thus, even within the limited scope of the social insect literature, two alternative and incompatible definitions of self-assembly exist, and both of these conflict with use of the term in other sciences. Clearly, there is a need for resolution. We discuss qualitative stigmergy further in example two.

In supramolecular chemistry, Lehn suggested that self-organization be reserved for dynamic multistable systems, while self-assembly be reserved for pattern formation processes tending toward equilibrium [2]. We adopt this suggestion as it provides a clear distinction between the terms, and is also consistent with the use of the term self-organization by Prigogine in describing nonequilibrium systems. This distinction is also consistent with Gerhart and Kirschner's [42] insightful discussion of both processes. They describe self-assembly as an energy minimization process that generates a single well-defined structure, uniquely determined by the size, number of components, geometry, and strength of interactions among components. In

contrast, they note that self-organization is characterized by rules that tend to be more general and structures more variable. They also note that self-organization typically generates structures under a wider set of conditions while the stability of these structures is accompanied by energy dissipation and gain and loss of material [42].

Self-assembly in chemistry very often employs noncovalent interactions such as hydrogen bonds, ionic interactions, metal chelation, and other molecular interactions. Such interactions are often weaker than covalent bonds and are reversible, so that the final structure is in thermodynamic equilibrium with its components [47]. Because of the generally reversible nature of the interactions between components, self-assembled systems have an inbuilt capability for error correction, which is typically not available to covalently bonded structures [47]. Often this is achieved by a random thermal effect, although external energy sources may also be used (see microtubule discussion later).

If generalized to apply across all the sciences, it's clear that self-assembly requires the components to remain essentially unchanged throughout the assembly process. This requirement makes it clear why the science of chemistry is not simply the science of self-assembly. Much of chemistry concerns interactions (reactions) where the products are not simple assemblages of components but are distinct, new entities.

The requirement that components remain unchanged throughout the self-assembly process has important implications for our understanding of emergence (which we discuss in more detail in a separate paper). Although emergence is colloquially understood as "the whole is something over and above its parts, and not just the sum of them all," we distinguish two classes of emergent phenomena [48]. Simple emergent properties are those collective properties that exist in systems at

or near thermodynamic equilibrium. Such properties are often close to linear and relatively predictable from the properties of the components. In contrast, complex emergent properties are those collective properties that exist in nonequilibrium systems and are dependent on a continual supply of energy or matter. Such properties are not easily reducible to the behavior and interaction of system components and may be formally incomputable. Self-assembled materials correspond to simple emergent properties for at least two reasons. First, their formation does not depend on nonequilibrium conditions. Second, since component parts remain unchanged throughout the assembly process, the collective self-assembled structure is linearly reducible to component parts.

Apart from the thermodynamic difference between self-assembly and self-organization, there are other important differences between these complementary pattern formation mechanisms. For self-assembly processes, it is the initial differences and/or specific relationships among components that encode the global order of the assembled whole. In other words, the dynamic interactions that occur during any self-assembly process reflect specific properties of component parts that interact with other components in directional and specific ways. In contrast, in self-organized systems initial encoding and differences among components are not required [42, 45]. Indeed, a characteristic feature of many self-organizing systems is the sudden onset of patterning in an initially homogeneous system [18, 19, 38].

Another subtle difference between self-assembly and self-organization concerns the minimum number of units required to produce collective order. It is often stated that, for self-organization to occur, there must be a minimum number of individuals [3, 17]. Although this is not necessarily the case (some biological systems with very few individuals nonetheless self-

organize in a biologically relevant manner [49]), it is correct that for many self-organizing systems a threshold exists below which patterning does not occur. In contrast, self-assembled systems do not appear to have a minimum size requirement. For example, hydrogen-bonded dimers and trimers have very few components.

Distilling the definitions of self-assembly, and the differences between self-organization and self-assembly proposed in the literature, we define self-assembly in terms of equilibrium and thermodynamic arguments. It is also clear that the process entails several additional features:

- a set of components that are encoded with specific and directional information on how they should interact with other components;
- interactions between components and partially assembled substructures being thermodynamically favorable;
- an element of reversibility in the interactions, allowing stochastic (e.g. random thermal) processes to explore interaction space and potentially locate a more favorable geometry;
- an equilibrium final structure when all components are “used up,” or when no more can be added because of thermodynamic or other constraints.

Self-assembly is a nondissipative structural order on a macroscopic level, because of collective interactions between multiple (usually microscopic) components that do not change their character upon integration into the self-assembled structure. This process is spontaneous because the energy of unassembled components is higher than the self-assembled structure, which is in static equilibrium, persisting without the need for energy input.

EXAMPLES THAT SPAN BOUNDARIES

Certain examples of decentralized pattern formation deserve special men-

tion, either because of their history or because they highlight the complex nature of the boundary between mechanisms of self-organization and self-assembly. Notably, magnetization and crystallization have historically been considered classic examples of self-organization [7]. However, these systems display order even when thermodynamically closed at or near equilibrium. Once crystallized, for example, the order is stable and does not require energy input, unlike self-organizing systems for which the order collapses upon cessation of energy input. We discuss magnetization in more detail later.

Conspicuously, many natural phenomena involve intimate interaction between self-organization and self-assembly. In biological systems, self-assembly and self-organization often operate on different spatiotemporal scales, together generating highly complex hierarchical architectures [42, 43]. In cells, for example, some dynamic components are self-organized [13, 14, 50–54], while other structures self-assemble in precise locations and at particular times [55]. In addition, although self-assembly implies systems tending toward equilibrium, it often occurs in nonequilibrium conditions (e.g. in the presence of continuous flows of heat and chemical reactions [43]). For example, microtubules are highly dynamic structures that self-assemble and disassemble rapidly. Although the self-assembly of microtubules does not require energy, their disassembly does. The energy is provided by hydrolysis of GTP by tubulin, which is an enzyme as well as being a structural protein [42]. The energy continuously destabilizes the self-assembled microtubules, which subsequently disassemble and shrink back toward the organizing centers from which they originate [42]. Thus, the whole system undergoes dynamic instability, in which some microtubules are growing rapidly while others are

shrinking rapidly [42, 56]. Dynamic instability is an interesting example of a self-organized process that is mediated by self-assembly. This process is further influenced by external templates [57].

An important contribution was recently made by Lefever [58] and Yamaguchi et al. [43], who highlighted the potential for overlap between the processes of self-assembly and self-organization. They considered “self-organization assisted self-assembly” and “self-assembly assisted self-organization” [43]. An example of the former might be the self-assembly of ribosomes assisted by self-organizing networks of molecular motors that traffic units around the cell. Other examples might include the self-assembly of spicules in sponges and silica crystals in grass, both of which may be assisted by self-organizing networks of various kinds. An example of self-assembly assisted self-organization is the dynamic instability of microtubule populations within cells.

MAGNETIZATION

The details of magnetization have been well described elsewhere [38, 59–62]. Historically, magnetization has been considered a classic example of self-organization [7]. However, a magnet held at its Curie point is an equilibrium system [7]. The characteristic order of magnetic domains is an interesting case that has features of both self-assembly and self-organization. A magnetic material is a closed, isothermal system whose temperature is below the Curie point, and exhibits a characteristic, average, domain size that represents an equilibrium between the randomizing influence of thermal motions and energetically favorable alignment of the magnetic dipoles. As the temperature decreases, the average domain size increases, and the average domain size will vary with temperature. In contrast, self-assembled struc-

tures retain their final structure over a range of temperatures, even at absolute zero. However, according to our definition of self-organization, the domain structures remain essentially constant (on average) at a constant temperature in a closed isothermal system. There is no requirement for constant energy or material input to maintain the domain structures (i.e., the domain structures are not dissipative). Hence, if one adopts our definition of self-organization, which requires nonequilibrium conditions, magnetization is not self-organized.

Nonequilibrium requirements notwithstanding, it could also be argued that because external conditions (temperature and pressure) must be fine-tuned, such systems cannot be self-organized. Similar criticisms have been made about the requirement of specific driving forces in self-organized critical systems (see references in [63]).

QUALITATIVE STIGMERGY

In the context of social insect behavior, where stigmergy was first introduced, the behavior of insects is modified by stimulating features of the environment. These behavioral changes in turn modify the stimulating environmental features establishing a feedback loop. The modified stimuli influences the behavior of individuals, creating an indirect communication channel

through a dynamically evolving environment. The role of the environment is therefore essentially an external memory resource [64]. This process is called stigmergy [65] and can be one of two types: qualitative or quantitative [18]. Quantitative stigmergy is where the stimuli involved are quantitative in nature, and often self-organized. For example, pheromone trails in ant colonies are based on chemical species that vary quantitatively and are self-organized. In contrast, qualitative stigmergy depends on a variety of stimuli that elicit a variety of behavioral responses. In other words, qualitatively different stimuli result in qualitatively different responses [18]. An example of qualitative stigmergy is nest building in wasps [18]. The specificity of the discrete sets of stimuli inspired use of the term self-assembly, because from the viewpoint of building elements, self-assembly mediated by the individual, is taking place. Building elements self-assemble whenever appropriate stimuli are received by builders. The details of these processes have been discussed elsewhere [17–19].

Because the apparent self-assembly of building materials is mediated by individuals, we suggest that qualitative stigmergy is best called agent-assisted self-assembly. This highlights similarities between true self-assembly and that of qualitative stigmergy while

acknowledging the fundamental differences between these system in terms of the force driving the self-assembly process. In genuine self-assembly processes, energy minimization drives the procedure, whereas in the context of qualitative stigmergy, it is the animal's behavior and motivation that drives the assembly process.

CONCLUSION

Self-assembly and self-organization describe pattern formation mechanisms that transcend scientific boundaries. We present a simple description of the two processes that should be applicable to most (if not all) scientific disciplines. We also discuss examples that have either been misclassified or that are difficult to assign unambiguously to one process or the other. As the importance of self-assembly and self-organization in biology is increasingly appreciated, we may discover ways in which they typically interact with natural selection. Indeed, it may one day even be possible to integrate these pattern forming mechanisms into the one general theory of pattern formation in nature.

ACKNOWLEDGMENT

Thanks to Martin Burd for critical review of manuscript.

REFERENCES

1. Goldenfeld, N.; Kadanoff, L.P. Simple lessons from complexity. *Science* 1999, 284, 87–89.
2. Lehn, J.-M. *Supramolecular Chemistry*; Weinheim: New York, 1995.
3. Nicolis, G.; Prigogine, I. *Self-Organization in Nonequilibrium Systems*; Wiley: New York, 1977.
4. Prigogine, I.; Stengers, I. *Order Out of Chaos: Man's New Dialogue with Nature*; Bantam Books: New York, 1984.
5. Ashby, W.R. Principles of the self-organizing dynamic system. *J Gen Psych* 1947, 37, 125–128.
6. Kushner, D.J. Self-assembly of biological structures. *Bacteriol Rev* 1969, 33, 302–345.
7. Heylighen, F. The science of self-organization and adaptivity. In: *The Encyclopedia of Life Support Systems (EOLSS), Knowledge Management, Organizational Intelligence and Learning, and Complexity*; Developed under the Auspices of the UNESCO; Eolss Publishers: Oxford, UK, 2003.
8. Skår, J. Introduction: Self-organization as an actual theme. *Phil Trans R Soc Lond A* 2003, 361, 1049–1056.
9. Coveney, P.V. Self-organization and complexity: A new age for theory, computation and experiment. *Phil Trans R Soc Lond A* 2003, 361, 1057–1079.
10. Gorshkov, V.G.; Makaréva, A. M. On the possibility of physical self-organization of biological and ecological systems. *Dokl Biol Sci* 2001, 378, 258–261.

11. Coveney, P.V.; Highfield, R.R. *Frontiers of Complexity*; Faber and Faber: London, 1996.
12. Coveney, P.V.; Fowler, P.W. Review. Modelling biological complexity: A physical scientist's perspective. *J R Soc Interface* 2005, 2, 267–280.
13. Misteli, T. The concept of self-organization in cellular architecture. *J Cell Biol* 2001, 155, 181–185.
14. Howard, M.; Kruse, K. Cellular organization by self-organization: Mechanisms and models for Min protein dynamics. *J Cell Biol* 2005, 168, 533–536.
15. Nicolis, G. *Introduction to Nonlinear Science*; Cambridge University Press: Cambridge, 1995.
16. Haken, H. *Synergetics*; Springer-Verlag: Berlin, 1977.
17. Bonabeau, E.; Theraulaz, G.; Deneubourg, J.-L.; Aron, S.; Camazine, S. Self-organization in social insects. *Trends Ecol Evol* 1997, 12, 188–193.
18. Bonabeau, E.; Dorigo, M.; Theraulaz, G. *Swarm Intelligence: From Natural to Artificial Systems*; Oxford University Press: New York, 1999.
19. Camazine, S.; Deneubourg, J.-L.; Franks, N.; Theraulaz, G.; Bonabeau, E. *Self-Organization in Biological Systems*; Princeton University Press: New Jersey, 2001.
20. Collier, T.C.; Taylor, C. Self-organization in sensor networks. *J Parallel Distrib Comp* 2004, 64, 866–873.
21. Hemelrijk, C.K. Understanding social behaviour with the help of complexity science. *Ethology* 2002, 108, 655–671.
22. Rosengren, R. Structures in ant colonies. *Arpakannus* 2001, 2, 13–18.
23. Anderson, C. Self-organization in relation to several similar concepts: Are the boundaries to self-organization indistinct? *Biol Bull* 2002, 202, 247–255.
24. Anderson, C. Self-organized behavior: Case studies. (Review of Camazine et al. 2001.) *Complexity* 2002, 7, 14–15.
25. De Wolf, T.; Holvoet, T. Emergence versus self-organisation: Different concepts but promising when combined. In: *Engineering Self Organising Systems: Methodologies and Applications (Lecture Notes in Computer Science)*; Brueckner, S.; Di Marzo Seruendo, G.; Karageorgos, A.; Nagpal, R., Eds.; Springer-Verlag: Berlin, Heidelberg, 2005; pp 1–15.
26. Sumpter, D.J.T. The principles of collective animal behaviour. *Phil Trans R Soc B* 2006, 361, 5–22.
27. Turing, A.M. The chemical basis of morphogenesis. *Phil Trans R Soc B* 1952, 237, 37–72.
28. Parrish, J.K.; Edelstein-Keshet, L. Complexity, pattern, and evolutionary trade-offs in animal aggregation. *Science* 1999, 284, 99–101.
29. Halley, J.D.; Winkler, D.A. Critical-like self-organization and natural selection: Two facets of a single evolutionary process? *Bio-Systems* 2008, 92, 148–158.
30. Gershenson, C.; Heylighen, F. When can we call a system self-organizing? In: *Advances in Artificial Life (7th European Conference, ECAL 2003, Dortmund, Germany)*; Banzhaf, W.; Christaller, T.; Dittrich, P.; Kim, J.T.; Ziegler, J., Eds.; Springer: Berlin, Heidelberg, 2003; pp 606–614.
31. Haken, H. *Synergetics*; Springer-Verlag, Berlin, 1977.
32. Haken, H. Synergetics as a strategy to cope with complex systems. In: *Interdisciplinary Approaches to Nonlinear Complex Systems*; Haken, H.; Mikhailov, A., Eds.; Springer-Verlag: Berlin, Heidelberg, 1992.
33. Bonabeau, E.; Theraulaz, G.; Deneubourg, J.-L.; Aron, S.; Camazine, S. Self-organization in social insects. *Trends Ecol Evol* 1997, 12, 188–193.
34. Bonabeau, E. Social insect colonies as complex adaptive systems. *Ecosystem* 1998, 1, 437–443.
35. Blazis, D.E.J. Introduction: The limits to self-organization in biological systems. *Biol Bull* 2002, 202, 245–246.
36. Deneubourg, J.-L.; Goss, S.; Franks, N.; Pasteels, J.M. The blind leading the blind: Modelling chemically mediated army ant raids. *J Insect Behav* 1989, 2, 719–725.
37. Sober, E. *The Nature of Selection. Evolutionary Theory in Philosophical Focus*; MIT Press: Cambridge, 1984.
38. Ball, P. *The Self-Made Tapestry*; Oxford University Press: New York, 2001.
39. Whitesides, G.M.; Grzybowski, B. Self-assembly at all scales. *Science* 2002, 295, 2418–2421.
40. Zhang, S.; Altman, M. Peptide self-assembly in functional polymer science and engineering. *React Func Polym* 1999, 41, 91–102.
41. Böhringer, K.F.; Srinivasan, U.; Howe, R.T. Modeling of capillary forces and binding sites for fluidic self-assembly. *IEEE* 2001.
42. Gerhart, J.; Kirschner, M. *Cells, Embryos, and Evolution*; Blackwell Science: MA, 1997.
43. Yamaguchi, T.; Suematsu, N.; Mahara, H. Self-organization of hierarchy: Dissipative-structure assisted self-assembly of metal nanoparticles in polymer matrices. *Nonlin Dyn Polym Syst* 2004, 869, 16–27.
44. Miller, A. Self-assembly. In: *The developmental Biology of Plants and Animals*; Graham, C.F.; Wareing, P.F., Eds.; Blackwell Scientific Publications: Oxford, 1976; pp 249–269.
45. Sendova-Franks, A.B.; Franks, N.R. Self-assembly, self-organization and division of labour. *Phil Trans R Soc B* 1999, 354, 1395–1405.
46. Anderson, C.; Theraulaz, G.; Deneubourg, J.-L. Self-assemblages in insect societies. *Insect Soc* 2002, 49, 99–110.
47. Lindoy, L.F.; Atkinson, I.M. Self-assembly in Supramolecular Systems; The Royal Society of Chemistry: Cambridge, UK, 2000.
48. Halley, J.D.; Winkler, D.A. Classification of emergence and its relation to self-organization. *Complexity* 2008, 13, 10–15.
49. Halley, J.D.; Burd, M. Nonequilibrium dynamics of social groups: Insights from foraging Argentine ants. *Insect Soc* 2004, 51, 226–231.
50. Kurakin, A. Self-organization vs watchmaker: Stochastic gene expression and cell differentiation. *Dev Genes Evol* 2005, 215, 46–52.
51. Kurakin, A. Self-organization versus watchmaker: Stochastic dynamics of cellular organization. *Biol Chem* 2005, 386, 247–254.

52. Coffey, D.S. Self-organization, complexity and chaos: The new biology for medicine. *Nat Med* 1998, 4, 882–885.
53. Auffray, C.; Imbeaud, S.; Roux-Rouquie, M.; Hood, L. Self-organized living systems: Conjunction of a stable organization with chaotic fluctuations in biological space-time. *Phil Trans R Soc Lond A* 2003, 361, 1125–1139.
54. Kurakin, A. Stochastic cell. *IUBMB Life* 2005, 57, 59–63.
55. King, J. Regulation of structural protein interactions as revealed in phage morphogenesis. In: *Molecular Organization and Cell Function. Biological Regulation and Development*; Goldberger, R., Ed.; Plenum: New York, 1980; pp 101–132.
56. Mitchison, T.; Kirschner, M. *Nature* 1984, 312, 237–242.
57. Liu, Y.; Guo, Y.; Valles, J.M.; Tang, J.X. Microtubule bundling and nested buckling drive stripe formation in polymerizing tubulin solutions. *Proc Natl Acad Sci USA* 2006, 103, 10654–10659.
58. Lefever, R. Workshop on Dissipative Structures and Non-equilibrium Assisted Self-Assembly, Foundation des Treilles, Tourtour, 2000.
59. Ward, M. *Universality: The Underlying Theory Behind Life, the Universe and Everything*; Pan Books: London, 2001.
60. Jensen, H.J. *Self-Organized Criticality*; Cambridge University Press: UK, 1998.
61. Binney, J.J.; Dowrick, N.J.; Fisher, A.J.; Newman, M.E.J. *The Theory of Critical Phenomena*; Clarendon Press: Oxford, 1992.
62. Haken, H. *Synergetics*; Springer-Verlag: Berlin, 1983.
63. Halley, J.D.; Warden, A.C.; Sadedin, S.; Li, W. Rapid self-organized criticality: Fractal evolution in extreme environments. *Phys Rev E* 2004, 70, 036118.
64. Beckers, R.; Holland, O.E.; Deneubourg, J.-L. From local actions to global tasks: Stigmergy and collective robotics. In: *Artificial Life IV (Proc Fourth International Workshop on the Synthesis and Simulation of Living Systems, Brooks, R.A.; Maes, P. Eds.; MIT Press, Cambridge, Massachusetts, July 1994)*; pp 181–189.
65. Grassé, P.-P. La reconstruction du nid et le coordinations inter-individuelles chez *Bellicositermes natalensis* et *Cubitermes* sp. La theorie de la stigmergie: Essai d'interpretation du comportement des termites constructeurs. *Insect Soc* 1959, 6, 41–84.