Autopoietic systems: The term 'autopoiesis' (from Greek $\alpha\upsilon\tau o$- (auto-), meaning 'self', and $\pi o\iota\eta\sigma\iota\varsigma$ (poiesis), meaning 'creation, production') refers to a system capable of reproducing and maintaining itself. The term was introduced in 1972 by the Chilean biologists Humberto Maturana and Francisco Varela to define the self-maintaining chemistry of living cells. Their definition of an autopoietic machine (in [MV80] p. 78) was:

'An autopoietic machine is a machine organised (defined as a unity) as a network of processes of production (transformation and destruction) of components which: (i) through their interactions and transformations continuously regenerate and realise the network of processes (relations) that produced them; and (ii) constitute it (the machine) as a concrete unity in space in which they (the components) exist by specifying the topological domain of its realisation as such a network.'

Arguably, Organic Computing systems can be regarded ultimately as autopoietic machines.

It should have become clear by now that the term 'system' and the corresponding abstraction is quite useful for the description of complex compounds. After all, our objective is the organisation of complexity. Traditionally, complexity is mastered by partially hiding information with subsequent iterated refinement. The result of this strategy is a hierarchy. If we add the property of nesting and containment, we arrive at a special form of a hierarchy, a so-called holarchy. The following section discusses the general notion of complexity and the two specific techniques in this context: hierarchies and holarchies.

3.3 Organising Complexity: Hierarchies and Holarchies

Ada Diaconescu

3.3.1 Complexity

Complexity is a rather broad concept, employed with different meanings in a wide variety of contexts. A commonly-agreed definition of *complexity*, and of the way(s) to measure it, does not exist at this time. The same applies to complexity's opposite – *simplicity*. Moreover, since the term *complexity* is employed to refer to rather different concepts, a unified definition would most likely be confusing.

Within the scope of this section, we aim to provide an overview of the most common conceptions of complexity and of the measures for capturing it; and to highlight the main implications of complexity for engineered systems. Where applicable, we also attempt to compare some of these views of complexity, so as to provide an intuitive bigger picture of this vast concept. Readers interested in more details on this broad topic (and interrelated concepts, such as *chaos* and *entropy*) can refer to the many discussions and analyses available from the literature (see Further Reading).

Common dictionary definitions of ‘complexity’ refer to two main types of concepts: i) some kind of *difficulty* related to an entity’s comprehension, description or functioning; and, ii) an entity’s composition of *multiple interconnected parts*. These concepts are not unrelated, since most difficulties associated with an entity (or system) stem from its internal structure, or composition from interlinked parts. We focus on developing these two concepts and their interplays next.

Within Computer Science (CS), different types of complexity have been related to various forms of *difficulty*. These include the difficulty of describing an entity; or, the resources necessary for a process to compute an entity; or, the difficulty of finding the process that computes an entity. Let us have a brief look at some of the most prominent examples of such complexity measures in CS. *Algorithmic complexity* estimates how fast or slow an algorithm performs, in number of steps, depending on the size of its input (cf. “Big O” notation, or Landau symbols).

From a different perspective, as a form of description complexity, the *algorithmic information complexity (AIC)* of a string of symbols represents the length of the shortest computing program that generates that string as an output. The more ordered the string – meaning, the more regularities it features – the shorter the program that generates it. Incompressible strings are equivalent to random ones, since their generating programs become as long as the strings themselves. This measure of complexity has been proposed independently by Kolmogorov (most well-known, hence often referred to as *Kolmogorov complexity*), Chaitin, and Solomonoff (cf. [Edm99], [Cou07]). As it can be easily related to *disorder* this type of description complexity is often associated with the concept of *entropy*, coming from physics (Section 4.2). Similarly, as a measure of information, it has also been associated with information entropy.

Another notable example of a complexity measure is *computational complexity*, which estimates the *difficulty* of a computational problem, depending on the resources needed to resolve it (e.g. processing and memory), irrespectively of the algorithm employed. Associated measures include the *logical depth* of an object – i.e. the time taken by a standard universal computer to generate the object; and the (inverse concept of) *crypticity* of an object – i.e. the time needed for a computer to compute the shortest program that will generate that object [Gel95]. In comparison to description complexity, these measures focus on the complexity of the process rather than that of the result.

The above kind of difficulties are exacerbated when instead of a single entity, or algorithm, we are dealing with a *system* of such entities interconnected with each other. Here, complexity typically stems from the system’s internal *structure*. Hence, a system is considered complex if it consists of multiple components that are interrelated in some intricate way – where ‘multiple’ and ‘intricate’ are relative terms. At the same time, component interrelations are typically *non-linear*, meaning that the overall system behaviour is different from the sum of behaviours of its components. Consequently, the system’s large component numbers, and, most importantly, their interconnections, make the system’s overall behaviour difficult to understand, to model and to predict (e.g. [Nel76], [Bar00], [Var09]). Complexity can be further increased if the system structure involves several *scales*, which are also interdependent [Bar00], [Var09].

A general definition reflecting this structural view of complexity is provided in [Edm99] '*Complexity is that property of a model which makes it difficult to formulate its overall behaviour in a given language, even when given reasonably complete information about its atomic components and their inter-relations.*' This definition considers complexity as a global characteristic of a (model of a) system, and relates the difficulty to formalise the whole system to the difficulty to formalise the system parts (in the same language). In other words, system complexity is viewed as the gap between the knowledge of individual components and the knowledge of the entire (emergent) behaviour (emergence was discussed in Section 4.2). An interesting related concept is that of 'connectivity' complexity. This complexity measure indicates that the more interconnections a system features internally, the more difficult it is to decompose it without altering its behaviour [Edm99].

Surely, most of the complexity criteria discussed above are actually quite subjective, as they are both context- and observer-dependent. Considering description complexity for instance, even if a system could, in fact, be described in simple terms, e.g. because of its regularities, a particular observer may fail to find those regularities and hence specify the system in a complex way instead. Also, a system's description complexity may depend on whether one describes the observed system's state (or behaviour), or, the underlying process generating that state (or behaviour). For instance, one may try to describe an image representing a Fractal by specifying all its pixels individually or trying to find a pattern therein (i.e. complex description of system state), rather than specifying the simple rules that generated it, such as a Mandelbrot set (i.e. simple description of a generating process). Interestingly here, a simple process, or description, may generate complex results – e.g. see the discussion on simple models for complex systems in [Var09].

Another interesting case is that where simple processes depend on external inputs (e.g. from their environment), which may lead to their resulting behaviour being complex in a complex environment, and simple in a simple environment. For instance, the complexity of a ball's trajectory when rolling down a slope depends on the complexity of the terrain, weather conditions, interference from other entities, and so on – this external complexity does not change the internal complexity of the ball (which remains simple), only of its resulting behaviour (complex trajectory). Conversely, finding the simple process(es) that can generate a targeted complex result may, in itself, be a difficult (or complex) process.

Complexity measures are also relative in that they depend on the units selected, in terms of granularity or accuracy. For instance, describing a software system via its coarse-grained components is simpler than via its programming primitives, which is in turn simpler than via its binary representation. Similarly, it is simpler to describe a gas via an aggregate average measure, such as pressure or temperature (more abstract), rather than via the trajectories of its individual molecules (more accurate). Since there are no absolute values for determining a system's complexity, the above criteria are mainly useful for comparing the complexity of different systems, along various dimensions.

Since this is a vast subject, several research domains focus on studying particular aspects of complexity, including non-linear dynamics (differential equations, attractors, chaos and stability analysis), networked systems (e.g. complex networks topologies such as scale free, community or small world – see Subsection 2.2.7; dynamic adaptive networks; graph theory), pattern-formation (e.g. cellular automata, self-replication and differentiation, reaction-diffusion systems), evolution and adaptation (genetic algorithms, evolutionary computing, neural networks, artificial life), collective behaviour (swarm intelligence, ant colony optimisation, decentralised synchronisation, phase transition) and cybernetics (self-regulation via feedback loops).

The above views on complexity, as relating to some sort of difficulty, are the most common ones in Computer Science (also adopted in this book). From this perspective, complexity is a problem to be avoided, or managed, since it hinders system understanding, modelling, controlling and/or engineering. In computing systems, complexity generally stems from several factors, notably including: the multitude of objectives, or functions, that the system must attain for its stakeholders; the large number of system components, often highly heterogeneous and distributed; and, the dynamicity of the system's internal resources, external environment, and stakeholder objectives, thus constantly requiring system changes (increasingly at runtime).

Relatively recent research areas such as Organic Computing [TSM17], and also Autonomic Computing [KC03], Self-Adaptive Systems [Che+09], or Self-Aware Computing Systems [Kou+17], aim to alleviate this complexity problem by enabling systems to self-manage (i.e. to change by themselves). While similar in purpose, these areas differ in their focus and approach to tackling this vast problem.

A particular view of system complexity, which may greatly help address this problem for engineered systems, considers that system complexity implies additional properties on global system behaviour and underlying structure, which, seemingly paradoxically, can render it simpler to external observers (e.g. [Cot09], [Bar00], [Sim76]).

One such key structural characteristic consists in the strong interconnections among components (internal) when compared to interconnections between components and their environment (external) and/or to themselves (self) [Cot09], [Sim62]. This characteristic can cause external influences on any one component to be highly impacted, or overpowered, by the internal dynamics, due to links with other components. Hence, the system behaviour overall is influenced by both external input and internal interrelations, in a way that decreases the domain of its external control. In other words, the overall system can be controlled with fewer degrees of freedom than it could initially, based on the separate degrees of freedom of each one of its components [Cot09]. This implies the existence (or emergence) of internal (self-)organisation, which enables components to achieve, via collective action, a system-level (emergent) property, or behaviour, that they could not reach individually. From an external perspective, the system features fewer global states when compared to the combinatorial set of states of its individual components.

This perspective on the importance of system connectivity to its internal resilience seems compatible with the relatively recent findings on the controllability of complex networks [LSB11]. Here, the authors correlated the ability to guide the dynamics of a complex network to the degree distribution of its nodes – where the degree of a node is given by the number of its links. Results indicated that sparse inhomogeneous networks were difficult to control whereas dense homogeneous ones could (only) be controlled via relatively few nodes, which, interestingly, were not the high-degree nodes.

While in these examples the interconnected nodes were quite basic, other examples seem to confirm the applicability of this view to systems that consist of more sophisticated entities, or *agents*. For instance, controlling the trajectory of a herd of sheep can be achieved quite easily, with a few shepherd dogs (or, more recently, drones), once the sheep have been gathered closely to each other, hence restricting the degrees of freedom of their individual movements. If sheep were widely spread, achieving the same result would probably take as many dogs as there were sheep to control. This particular view on system complexity also corresponds to the definition of semi-autonomy as discussed in Section 4.5. Namely, a system is semi-autonomous if it is controlled via a reduced interface – i.e. by high-level goals rather than by low-level control signals.

In a way, this particular view of system complexity – i.e. (self-)organised complexity – seems to imply, paradoxically, that complex systems are those that appear to external observers as more stable (since less sensitive to external variations); and relatively simpler to describe globally (than expected considering the large numbers of internal components and their interconnections – i.e. its internal 'complexity', if complexity were viewed as difficulty, as discussed in the first part of this section). However, this paradox is only apparent, as it is explained by the difference in the level of abstraction, or granularity considered. Namely, a complex system may *appear* relatively simple to an external observer at the whole system level, whereas it is intricate at the fine-grained component level. It is precisely the intricate internal interconnections among individual components that lead to the relative global external simplicity. Please note that this does not make such complex systems globally simple in absolute, just relatively simpler, when compared to the entire combinatorial space of possibilities enabled in principle by internal components, if these were to evolve completely independently from each other. Also note that this does not mean that it is always easy to find the external system controls that will bring the system to a targeted global state or behaviour. These are still challenging questions for engineered complex systems.

This essential internal (self-)organisation characteristic enables such complex systems to be more robust with respect to changes in their environment (since less sensitive to external influence). A special kind of such systems, also referred to as Complex Adaptive Systems (CAS) [Hol96], [Gel95], are able to maintain relatively stable internal states, by adapting to external changes (or inputs); and thus improving their survivability in unpredictable environments. A subcategory of such systems are also self-reproducing, meaning that they undergo a cycle of birth, growth and death (e.g. living organisms). Different works from the literature characterise complex (adaptive) systems via a wide variety of properties, without converging to a unique definition (such detailed discussion is outside the scope of this section – we focus on the common understanding of complexity only, without specifically referring to adaptability).

Importantly, the above characteristic also facilitates a system's composition with other systems, since the combinatorial search space of viable inter-system connections is much reduced by the relative simplicity of each system's external controls. This enables complex systems to form *nested structures*, where each system level can feature a different composition of complex sub-systems (further discussed below in Subsection 3.3.3). Most complex systems that we can observe in nature feature these characteristics – e.g. individual organisms formed by internal cells, atoms, quarks, gluons, etc., and also forming organisations, societies, economies, etc.

Another interesting characteristic sometimes associated with this type of complex systems is the alternating nature of component interrelation types, such as cooperation and competition, at successive levels of abstraction or scale [Bar00]. For example, members of different communities may self-organise internally (i.e. *cooperation* at community level), in order to rival with each other (i.e. *competition* at upper inter-community level). We can also consider that while each member is self-organised internally (i.e. cooperation among internal organs and cells), there is also some rivalry among members (i.e. competition among community members). This leads to an interesting *conflicting* situation for individual members, who may have to entertain both competition and cooperation relations within the community (further developed below in Subsection 3.3.3, when discussing the dual nature of holonic components; and in Subsection 5.3.3, when discussing goal conflicts). In [Nel76] such conflicts are at the very core of system complexity, as complex systems are defined to be those that pursue competing goals.

Intuitively, we can merge the two views of complexity discussed above as follows. The first one emphasises internal system intricacy (based on individual components and interconnections) which leads to some sort of difficulty in representing, executing and/or predicting its global (emergent) behaviour. The second view constrains the set of intricate systems defined by the first view to only those that, via particular internal (self-)organisations, exhibit relatively simpler behaviours to external observers (meaning a reduction in degrees of freedom and/or of description length). Of course, not all systems with intricate internal structures (first view) necessarily feature simpler global behaviours (second view). However, it is worth noting this special category of complex systems, which do exhibit simpler emergent behaviours based on intricate internal structures, since many autarchic and self-perpetuating systems we can observe in nature do feature this property [Sim62]. This should hardly be surprising, since these complex systems are the ones that would have been sufficiently stable, or viable, to survive long enough for us to be able to observe them. They can be of great significance to the engineering of OC systems, since they have already found solutions to the difficulties identified above – i.e. related to system scale, interconnections, unexpected change and so on. Section 4.5 discusses this effect in terms of an OC architecture constructed with the objective to generate an artificial system with exactly this property: reduced complexity as seen from the outside. Section 5.3 aims to identify and draw from such natural solutions in order to help engineer OC systems.

3.3.2 Hierarchy

Etymologically, hierarchy[4] has its roots in the Greek *hierarkhia* ('rule of a high priest') or Medieval Latin *hierarchia* ('ranked division of angels'). It has, over time, developed the meaning of 'ranked organisation of persons or things' – first recorded in the 1610s, initially referring to clergy.

Today, hierarchy represents a particular way of organising a set of entities – such as persons, items, concepts, symbols, and so on – so that each entity is either 'higher', 'lower' or at 'same level' with respect to the other entities (Fig. 3.5). Structurally, a hierarchy takes the form of a tree, with one root node being higher than all the other nodes. Alternative organisations that are non-hierarchical include for instance *heterarchies* – where entities are unranked, 'horizontal', all at the 'same level'. In computing systems, master-slave architectures represent hierarchies, whereas peer-to-peer systems are heterarchies.

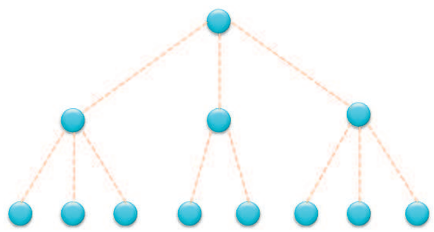

Fig. 3.5: Hierarchy – a partially ordered set of entities

The exact semantics of a hierarchical organisation may vary, carrying diverse implications, which may or may not occur simultaneously within any one hierarchy. These semantic implications chiefly concern the *nature of the relations* between entities at 'higher' hierarchical levels and entities at 'lower' hierarchical levels. In computing systems, such inter-level relations may represent (e.g. [Dia+16]):

- *Topology*: higher-level entities communicate with or contain lower-level entities; the overall system topology is typically a tree (but can also be extended to a directed acyclic graph, where several entities occupy the highest level);
- *Authority*: higher entities have authority and control over lower entities;
- *Scope*: higher entities have a larger field of view and action than lower entities;
- *Abstraction*: higher entities have a coarser granularity of observation, modelling and action than lower entities.

[4] Online Etymology Dictionary: http://www.etymonline.com/index.php?term=hierarchy

Additional types (or semantics) of hierarchical relations may exist in various systems. For instance, in social systems hierarchies can signify different degrees of individual status, wealth, needs, values, and so on.

Within a hierarchical system, the above concerns may overlap or may be orthogonal (e.g. combined in various ways). For instance, the root(s) of a hierarchical topology may or may not have more authority, larger scopes and higher abstraction compared to child and leaf nodes.

3.3.3 Holarchy

This subsection introduces the concept of *holonic system* (or *holarchy*), as observed in complex natural systems, emphasising their defining structural properties and their implications on system autonomy. These concepts are drawn mainly from Herbet Simon's insights into the importance of hierarchical structures and stable intermediate forms in the evolution and survival of complex natural systems; and from Arthur Koestler's observations of such structures in living organisms, social organisations, and non-physical entities; and finally, from Koestler's realisation of the dual nature of all entities making-up complex systems, as both wholes and parts, which led him to coin the term 'holon'.

We will capitalise on this conceptual basis in Section 5.1 (Subsection 5.3.5), in order to analyse the common features of natural holonic systems, and to identify the key properties that appear to be behind their ability to develop, self-adapt and survive in complex competitive environments. We will then draw on these insights to provide a generic architectural model for facilitating the development and management of complex OC systems.

A *holonic structure* (or *holarchy*) is an encapsulated hierarchical structure, characterised by the fact that systems are composed of sub-systems, which are in turn composed of sub-sub-systems, and so on, recursively; and, at the same time, included into supra-systems, which are part of supra-supra-systems, recursively [Sim62], [Sim96].

Example: Holonic system in nature

Multi-cellular organisms are composed of cells, which are in turn composed of molecules, atoms and so on. At the same time, such organisms can be part of organised communities, societies, and so on.
Non-living entities may also feature such structures, including writings – composed of sentences, words and letters; pieces of music – composed of bars (or measures) and beats (or notes); or cultural ideas – composed of *memes* [Daw96].

In a holonic structure, from a purely topological perspective, the hierarchical relations between higher- and lower-level entities (Subsection 3.3.2) signify *containment* (rather than mere correlation or communication), as shown in Fig. 3.6. This implies that *holarchies* correspond to the subcategory of hierarchies commonly referred to as *nested hierarchies*, *containment hierarchies*, or *compositional containment hierarchies*. In addition, these relations may or may not imply higher authority, scope or knowledge. When representing the structure of complex natural systems, holarchic relations do usually signify higher abstraction of the containing entities with respect to the contained entities (as discussed in Subsection 5.3.4 when considering *holonic abstraction* properties).

Containment relations generally impact the visibility and accessibility of contained entities by other entities situated outside their containers. They can also impact the mobility of entities through containers, both for entering and for exiting a containing entity. Finally, and perhaps most importantly, containment impacts the default inter-dependence between the containing and the contained entities. Hence, actions of the containing entity can have an immediate impact on all its contained entities. For instance, in physical systems, such as an apple, the contained entities, such as the apple's molecules, atoms, fundamental particles, and so on, are physically interconnected, or interlinked; hence, moving the physical system engenders moving all its contained entities.

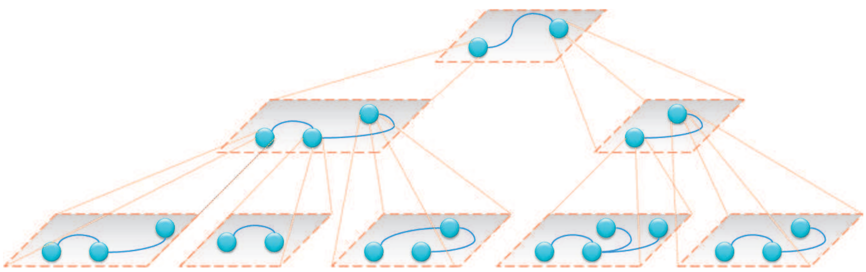

Fig. 3.6: Holarchy – recursively self-contained hierarchical system

Such hierarchy of holons is also called a *holarchy* (Fig. 3.6). Within such structure, each *holon* is a semi-autonomous entity playing a double role, or featuring a double nature, simultaneously [Koe67]:

- *Whole* nature: a holon is an autonomous self-sufficient *whole* controlling its parts (sub-holons). From this perspective, it is a self-contained, self-reliant unit that can survive within an environment independently of the higher-level holons that contain it. This means that it is a stable form, able to sustain itself (via self-* processes or autopoiesis [MV80]) despite external disturbances, within limits.
- *Part* nature: a holon is a dependent *part* of a supra-system. From this perspective, it provides an intermediate form for the functioning of larger forms (higher-level holons); and is hence subject to control from such supra-holons.

Certainly, unless a holonic system is open-ended, a subset of its entities will not feature this dual nature. Namely, "elementary" holons (lowest-level) and "top-level" holons (highest-level), only represent parts, or wholes, respectively. However, in most systems, elementary and top-level holons are rather relative, reflecting the observer's perspective, knowledge limitations and interest. For simplicity, we use the general term *holon* to imply an entity's dual nature as whole and part; and use the more specific terms of *supra-holon* and *sub-holon* to emphasise a holon's whole nature, or part nature, respectively.

Considering the dual nature perspective, supra-holons (wholes) cannot survive without their contained sub-holons (parts); whereas sub-holons (parts) can, in principle, survive outside their supra-holon context (see discussion below). Interestingly, this does not mean that a supra-holon necessarily depends on a particular set of holons for its survival, but merely on the presence of certain types of holons, and interconnections, irrespectively of the actual instances of those types and connections. This property is key to a holon's autonomy and self-sustainability, achieved via dedicated self-* processes (e.g. Sections 4.1 and 4.2). Such processes include the self-organisation of constituent entities, discovered opportunistically, so as to fulfil current necessities and to achieve self-optimisation and self-repair; self-adaptation to the environmental constraints and opportunities; and, self-protection against harmful external intrusions (or detrimental internal phenomena).

Example: Inter-dependence between holonic parts and wholes

hydrogen atoms (H) can exist outside water molecules (H_2O), whereas water cannot exist without its hydrogen atoms. At the same time, a water molecule can be formed with any hydrogen atoms.
Similarly, a society cannot exist without its members, yet an individual can, in principle, survive outside a society. At the same time, a society can survive the departure and joining of some members.

Based on the above considerations, we may categorise holons according to two main criteria: their degree of autonomy, and, of self-containment (Fig. 3.7). *Autonomous* holons are endowed with self-* processes that enable them to reach homoeostasis, with respect to certain properties or objectives. Conversely, *non-autonomous* holons are generally inert and non-reactive to changes. A holon's degree of autonomy is essential to its self-sustainability capabilities. This, in turn, enables it to become a relatively stable intermediate form on which supra-holons can be constructed.

Example: Autonomous vs non-autonomous holons

autonomous holons notably include living organisms and their social organisations. Non-autonomous holons include non-living systems, such as books or ideas.
Indeed, several discussable examples can be invoked of non-living systems that feature some degree of autonomy, such as viruses, snowflakes, sand-dunes or tornadoes – a detailed discussion of such subtleties is beyond this section's scope.

Considering the second criterion, autonomous holons can be either *self-contained*, such as individuals, or *border-less*, such as collectives or societies (Fig. 3.7). This criteria makes an important distinction with respect to the degree of independence of sub-holons [Akk10]. Namely, an *individual* holon is self-contained (within identifiable borders) and typically behaves coherently as if there were a single point of control, which coordinated all internal sub-holons (even if in reality several well-coordinated points of control may exist – e.g. [Min86]). This strong interdependence may, in some cases, have an impact on the survivability of sub-holons outside their individual holon, if their autonomy becomes limited to the particular environment ensured by their encapsulating holon.

In a *collective* holon (border-less – except, perhaps, for conventional borders), such as a human society or an ant colony, several centres of control must self-organise and coordinate explicitly, via built-in behaviours and/or intentional decision-making processes, in order to reach coherent behaviours at a global level. Here, the interdependence between the collective holon and its sub-holons is weaker (than in the individual holon), which means that sub-holons are less dependent upon, and hence more likely to survive, outside their supra-holon. Certainly, there is a discussable grey area in-between these two categories, with multiple degrees of interdependence, which are out of this chapter's scope.

For non-autonomous holons, self-contained holons are generally identifiable, inert objects. Border-less holons are merely heaps of unrelated objects, possibly correlated but not achieving any collective objective or purpose. Again, whether or not

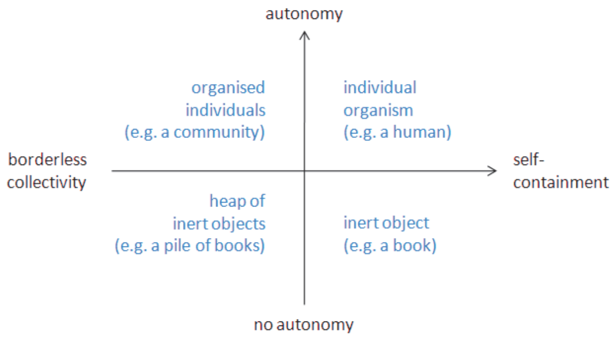

Fig. 3.7: Holon types – based on degree of autonomy and level of containment

such object heaps achieve a collective purpose may be relative to an external observer's perspective, and also context dependent.

Example: Individual vs collective autonomous holons

A single organism represents an *individual autonomous* holon, which is self-contained within an identifiable membrane, or skin organ; and features coherent behaviours, as if all its internal sub-holons were controlled by a central entity. Hence, when an organism moves (individual holon), this also incurs moving all its cells, molecules and atoms (sub-holons). In terms of part-whole inter-dependence, not only does an organism critically depend on its cells, but also a single cell extracted from a multicellular organism will typically not survive on its own. This, despite the fact that uni-cellular organisms do exist, and even if molecules and atoms can survive beyond the organism.
Human organisations, ant colonies, bee hives, fish swarms or bird flocks represent *collective autonomous* holons, which are coordinated by mere self-organisation (of individual member holons) rather than via an identifiable border or central controller. Generally, any individual member of the collective holon, such as one human, ant, bee, fish or bird, may survive outside the collective (for a while, at least). In some cases, individual members may also disintegrate their collective and reorganise into a different one, such as citizens reorganising into new societies.

Example: Individual vs collective non-autonomous holons

Individual non-autonomous holons (self-contained) are generally inert objects, such as books or ideas, and *collective non-autonomous* holons (borderless) are merely heaps of unrelated objects, such as piles of books or unrelated ideas.

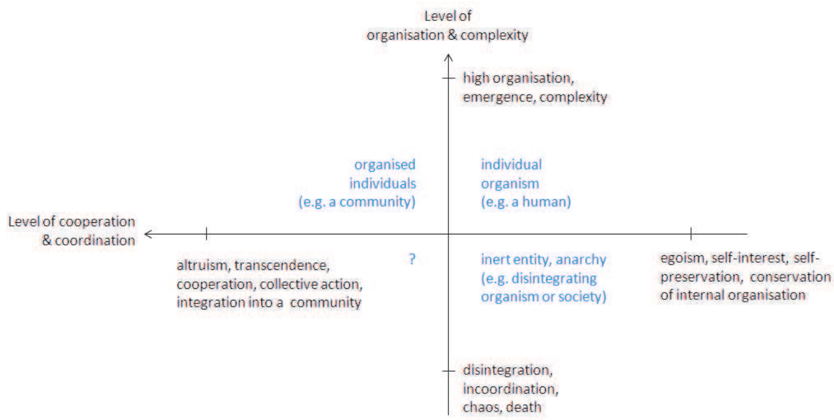

Fig. 3.8: Holon types – via levels of external cooperation and internal organisation

A similar, yet subtly different way of looking at different holon types is based on their level of cooperation with external holons and on the complexity of the resulting organisation (Fig. 3.8). Namely, when multiple holons cooperate and coordinate their actions, higher-level more complex organisations can form, or emerge. With respect to our previous holon categorisation (Fig. 3.7) organisations based on holonic cooperation can be both borderless or self-contained; and may survive autonomously depending on the ability of their holon members to adapt to internal and external changes.

An important consideration here is the extent to which a holon's behaviour is beneficial and/or detrimental to the objectives of its holonic collective (or supra-holon), as opposed to its own objectives. Several cases can be distinguished here, including: a) the individual objective *benefits* from the collective objective being pursued or achieved; b) the individual objective *suffers* from the collective objective being pursued or achieved; c) the individual objective both *benefits and suffers* from the collective objective being pursued or achieved, either at different times, or at the same time.

An interesting question can be raised about which entity of a holonic system actually benefits and controls the rest of the system (self-)organisation. Do individuals control the collective organisation for their common benefit? Does a subset of individuals control the collective for their own benefit, while harming the other individuals' objectives? Does the organisation control its individual members for its own survival? Examples of all the above cases can be found – for instance, in various societies, organisations, institutions, political and economic systems. Also, a system that starts off in one case can sometimes shift into other cases; or in a situation where several cases hold, as system parts and wholes become inter-linked and interdependent (see examples below).

This categorisation also points out to the fact that the coordination of cooperative holons in one layer leads to a higher-level organisation at the next layer up, hence to the formation of a supra-holon, and to an increase in complexity of the global holonic system. Hence, increasing organisation levels lead to an increasing complexity overall. At the same time, organisation at a certain level can help control and simplify that level for the next level up. When that is the case, the upper level can view and manage the underlying level via a reduced set of abstractions, ignoring its internal details (see Section 5.3). This enables increasing global complexity to be managed; and hence to further increase.

Example: Selfish versus cooperative holons

When cells coordinate their multiplication and behaviours they can form higher-level organisations, or organisms (i.e. autonomous and self-contained systems). Each cell may benefit from inclusion within the organism, in terms of its survival, because of the stable and well-adjusted environment ensured by the organism's homeostatic processes (e.g. suitable nutrients, temperature and pressure). For instance, animals consist of formerly independent bacteria that have lost a lot of their individual autonomy, yet gained the ability to act collectively so as to increase their chances of survival.

Surely, one can wonder to which extent it makes sense to apply labels such as 'selfish' or 'altruistic' to unaware entities such as cells, which may have little choice but to develop within an organism, as dictated by their DNA code and associated morphogenetic processes. At the same time, as argued for instance in Dawkin's theory of 'The Selfish Gene' [Daw96], one may wonder to which extent an organism's behaviour is tuned to pursue its own objectives, such as its individual survival, or its genes' objectives, such as their replication and survival over time. The question of who takes advantage of whom can become cumbersome indeed. Finally, any serious disruption in cell coordination leads to the organism's death.

At a higher organisational level, a self-aware individual may choose to join a collective, an institution, or a society, in order to gain individual advantages, such as protection or health-insurance; while also loosing some of their autonomy, such as having to abide by collective norms, regulations and laws. In other cases, individuals may join a collective solely for the common benefit, while totally sacrificing their individual interests; this may be voluntary (e.g. "heros") or via coercion (e.g. slaves). As before, higher-level organisations or societies seize to exist when the individual cooperation stops.

When the flow of information and/or material entities, and their interpretation and/or usage, between the holarchic levels is disturbed, coordination within the holarchy may begin to break and the holarchy overall may disintegrate, down to various depths of intermediate sub-holonic levels. In some cases, wholes may no longer recognise their essential dependence on their parts and hence exercise destructive control upon them (e.g. totalitarian regimes in societies; or, drug abuse in organisms). Similarly, parts may no longer recognise the coordinating authority of their wholes and act against them (e.g. anarchy in societies; or, auto-immune conditions in living organisms).

In holarchies where the degree of autonomy of members (selfish, or egoistic nature) and the degree of obedience towards their supra-holons (transcendental, or altruistic nature) can change, such as for a society's members, finding the right balance between these two aspects – selfish autonomy and collective obedience – is critical to the survival of the holarchy and of its holons, and can be a challenging, ongoing, self-adaptive process [Koe67], [DP14], [JPD15]. Indeed, only expressing the transcendental, collective-oriented nature may lead to massive actions aimed to benefit the collective, irrespectively of damages caused to (some of) its members (e.g. mass movements, or Plato's ideal state or Republic). Similarly, only expressing the selfish, individual-oriented nature may lead to progressive loss of shared culture, values and possibly to societal disintegration (e.g. Marx's criticism of unregulated capitalism).

Surely, various combinations of the categorisation criteria above, as well as of new criteria, can be devised to distinguish among the wide variety of holonic types.

Further Reading

For further details on complexity, the reader may refer to [Edm99] and [Cou07] for *definitions* of a wide diversity of complexity types; to [Wal92], [Gel95] and [Hol96] for discussions on *system complexity*; to [Cot09], [Sim62] and [LSB11] for *(self-)organised complexity* leading to simpler control; and to [Bar00] for relating these concepts to '*chaos*' and '*entropy*'.
A more extensive view into the ideas behind *hierarchical* and *holonic organisations* for complex systems can be obtained from [Sim62], [Koe67] and [Sim96].

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