Mediator Evolution: a general scenario for the origin of dynamical hierarchies

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ABSTRACT. A general scenario is proposed to understand the evolutionary transitions that lead to the emergence of higher level systems through the assembly of independent components. First, multilevel emergence is reviewed in general as the result of variation and selective retention of assemblies. It is emphasized that when the components are dissipative (e.g. living systems) the process is complicated by the on-going competition for scarce resources between the agents. While there is a selective pressure to achieve synergy, and thus avoid conflict, competition remains potentially present, leading to the free rider problem. To tackle this problem, a control must evolve to suppress conflict. This can be achieved by an exploiter (e.g. parasite) evolving to become a cultivator of the collective. The "exploiter" does not need to be an external invader, but can be a distributed mode of interaction or "aspect system" of the collective, that may co-opt external support. The detailed scenario is as follows: 1) a collective of agents interacts, constituting an interaction medium; 2) the medium coordinates the interactions, becoming a conflict mediator; 3) the mediator establishes active control over the agents, becoming a goal-directed manager. These proposed stages of an evolutionary transition are used to analyse a variety of concrete examples, including physical self-organization, spatial partioning of competing agents in biology, and the evolution of markets.

KEYWORDS: evolutionary transitions, emergence, hierarchy, dynamical systems, self-organization, competition, synergy, control, conflict mediation, aspect systems

1 Introduction

A dynamical hierarchy [33,10,24] is defined in the introduction to this special issue as a dynamical system with multiple levels of nested subcomponent structures, in which the structures and their properties at one level emerge from the ongoing interactions between the components of the lower level. The central issue is emergence: the appearance of high-level properties that cannot be reduced to a simple sum or aggregate of the properties exhibited by the components of the lower level. Thus, higher level components can be seen as wholes or "individuals" [30], i.e. systems that have an identity of their own which would be lost if the system would be decomposed into its parts.

Such hierarchies are ubiquitous throughout the physical, chemical, biological and social world. The present paper will try to understand the functioning of these hierarchies by analysing the evolutionary processes that led to their creation, i.e. the processes of variation and natural selection that result in the creation of a higher level system by the association of lower level components. This process has recently become a focus of study under the name of “evolutionary transition” [30, 28, 21] or “metasystem transition” [17, 38]. Examples include the formation of molecules out of atoms, of cells out of polymer assemblies, of multicellular organisms out of cells, and of societies out of individuals.

The paper will first review and define the fundamental concepts and mechanisms necessary to understand such transitions. It will then focus on the basic obstacle that must be overcome for a transition to be successful: the intrinsic conflict over resource consumption that exists between individual components and between lower level components and the emerging higher level. It will propose the principle of selective pressure for synergy to explain how evolution tackles this problem, pointing out its different effects on symmetric and asymmetric interactions. In particular, it will introduce the process of mediation as a very general, yet concrete, model of an evolutionary transition, which encompasses several more specific scenarios proposed by other authors.

2 Basic evolutionary transitions: a review

2.1 Attractor dynamics

Assume a collection of *components*, i.e. individual systems or agents that can interact with other systems. Examples of components are particles, molecules, cells or people. A component is a dynamical system that can take on different states s within a state space S under the influence of internal and external forces. This dynamics is in general indeterministic—or at least unpredictable—as we can never precisely observe all the factors that determine the outcome. The unpredictable trajectory $s(t)$ of a component visiting a variety of points s in its state space under the influence of known and unknown factors can be called *variation*.

The individual components together form a system, whose state space is simply the Cartesian product of the state spaces of the components:

$$S_c = \Pi_i S_i = S_1 \times S_2 \times \ldots S_n.$$

Any dynamic system undergoing unrestricted variation will sooner or later end up in an *attractor* of the dynamics, i.e. a subset $A \subset S$ that it can enter but not leave. Such irreversible transition is the essence of self-organization [22,13,9,1], since after entering the attractor the statistical entropy or uncertainty concerning the state of the system has been reduced, so that the system has become more ordered or predictable. The attractor imposes a *constraint* on the further variation of the system.

2.2 Emergent properties

A constraint on a system in general entails a covariation between its components: if one of the component systems varies, the other ones will have to vary within a limited range as well. The components have become mutually dependent, and will now vary together, rather than individually. For example, an individual atom can move freely through space, while the same atom bound into a molecule can only move if the rest of the molecule moves as well, since their mutual distance is fixed within a certain range. Covariation decreases the number of degrees of freedom, as the original variables describing these degrees of freedom have become co-dependent.

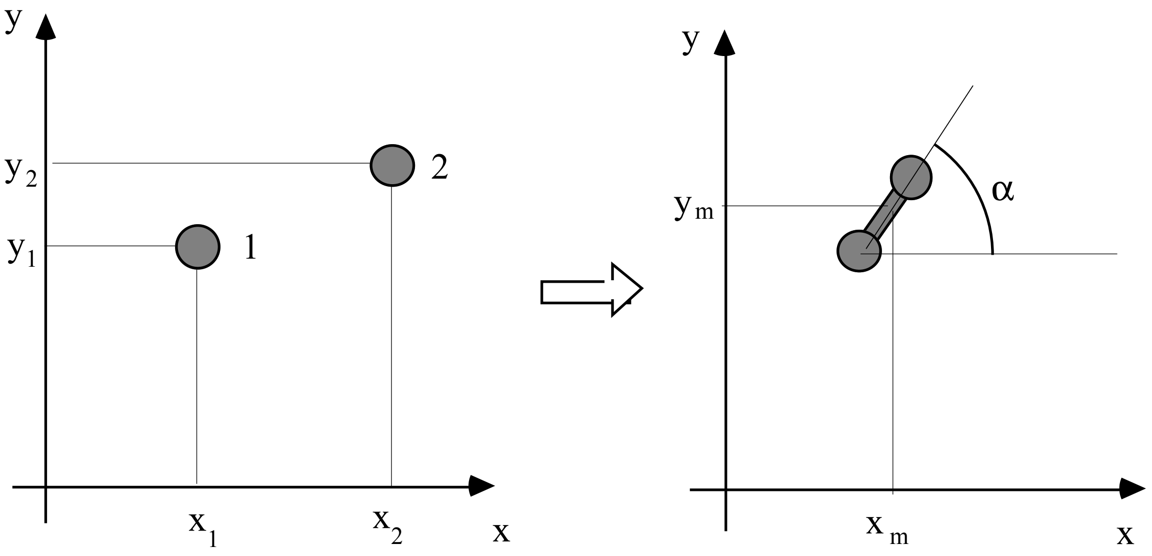

Fig. 1: left: two independent components 1 and 2 with their four defining variables x_1, y_1, x_2, y_2; right: the same components after they have become bonded and lost a degree of freedom (fixed distance between the components), resulting in three remaining variables: x_m, y_m and the angle α

Define a *property* of a component as the value of one of its variables (e.g. vertical position or speed). This implies that the process of bonding or self-organizing by changing the degrees of freedom creates new properties. For example, we would no longer describe the position of a two-atom molecule by the 2 × 3 spatial coordinates of its component atoms: (x_1, y_1, z_1, x_2, y_2, z_2) but by the 3-dimensional coordinates of its center of gravity, plus the two coordinates of its spherical orientation, given that the bonding has fixed the distance between the atoms. The variable “orientation” defines an *emergent property*: it does not exist for an individual atom, as it describes the state of the relation between the two atoms. The principle is illustrated in Fig. 1 for the simpler two-dimensional case, where orientation corresponds to the one dimensional variable “rotation angle”.

A multicomponent system entering an attractor can be seen on the lower level as a mutual adaptation [1], or fitting together [22, 12], of the individual components. This process can be conceived more concretely as follows. Two components, e.g. atoms or people, *interact*—meaning that they vary relative to each other, but so that the variation of the one to some degree influences the variation of the other. E.g., for atoms, the interactions are carried by the electromagnetic forces of attraction and repulsion; for people, by conversations and the social relations that grow out of these. Some of these relative states are preferred or *selected*, in the sense that it easier to enter them than to leave them. Once the components have entered into this mutual arrangement (attractor), they will tend to “stick” to it, and no longer be able to undergo certain types of relative variation (see Fig. 2). For example, a sodium atom (Na) and a chlorine atom (Cl) may form a chemical bond resulting in a salt molecule (NaCl). Two people who have been discussing may become committed to a particular type of relationship, entering into a contract, collaboration, friendship or marriage.

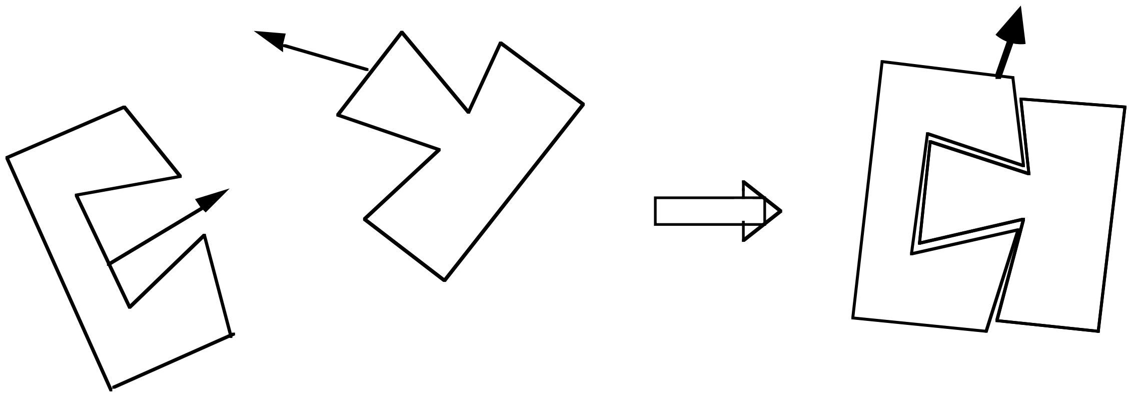

Fig. 2: illlustration of the process of bonding: the two independently moving components (left) have discovered a relative position in which they rigidly fit together (right), so that after the transition they can only move as a whole.

2.3 Hierarchical architectures

Generally, the attractor states or “fit” states constitute a mere fraction of the set of all states. Therefore the probability is small that a random interaction would result in the creation of such a bond. This applies in particular if more than two components are involved, since the probability of fitting together decreases exponentially with the number of components that need to discover the state that is fit relative to all others. This is why H.A. Simon in his classic paper on “The architecture of complexity” [34] argued that typical assemblies of components formed by random interaction are small, and that the only practical way to increase the size of the system is to have these small assemblies function as new components or “building blocks”, to produce higher level assemblies. Thus, Simon proposed an explanation for the *hierarchical architecture* of many evolved systems, which consist of many, nested components, forming a steep, narrow pyramid.

However, given the exponentially decreasing probability of encounter, even very small assemblies (more than three or so components) would seem to be highly unlikely. This is confirmed by the observation that practically all known chemical or physical reactions between particles, when analysed at the most elementary level, involve the encounter of not more than two components. In practice, chemical reactions in which more complex structures (e.g. polymers or crystals) are formed consist of subsequent steps, in which new components join an existing assembly one by one. In practice, this process often accelerates exponentially because of a positive feedback mechanism: the larger an assembly (e.g. a crystal or an ecosystem) becomes, the more anchoring points or “niches” it offers for additional components to fit in [18,12].

In contrast to the Simon scenario, such exponential growth of assemblies produces *flat* hierarchies, with many components per level and few levels. Moreover, to achieve *any* kind of hierarchy, we need a mechanism that will arrest this process of “horizontal” growth at some point, so as to create an opportunity for “vertical” emergence.

2.4 Closure

This mechanism may be called *closure*[4,15,21]: the assembly reaches a state in which the capacity for further interaction is somehow “used up”, i.e. no more degrees of

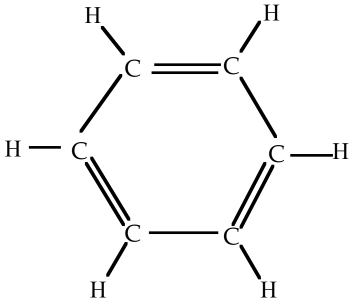

Fig. 3: a benzene molecule illustrating a "closed" assembly

freedom are left to vary relative to an as yet independent component so as find a mutually fitting state. A simple, visual illustration of such a situation is provided by a benzene molecule, consisting of a circular, closed chain of six carbon-hydrogen (C-H) monomers, where the last monomer of the chain is bonded to the first one (Fig. 3). In this configuration it is difficult for additional monomers to join. A social example is a soccer team—an assembly that by definition is limited to eleven people interacting in specific ways.

A more prosaic case of "closure" occurs when there simply are no more components available that could join the assembly, e.g. because they have already joined competing assemblies. An example is a crystal in a solution that stops growing when there are no more molecules of the right type in the solution, or a chess club that stops enlisting members when the remaining people in town either are not interested in chess or already belong to a rival chess club.

Closure is an essential concept for understanding emergent properties. Properties are in essence the values of variables that can be observed through interaction—with a measurement apparatus or with the senses. If a particular degree of freedom has become inaccessible to outside interaction because of bonding, then the corresponding property has become fixed, and lost its relevance. The variable has been "closed off" from the environment, and its values are no longer distinguishable from outside the system. But the system still has degrees of freedom, characterizing the system as whole rather than its individual components. These "global" variables allow the system to interact with other systems, but in a qualitatively different way. For example, a positively and a negatively charged particle interact directly via electrostatic attraction. However, once bonded, the electric charge of the whole is zero, and it can only interact via the more indirect dipole force, which depends on the fixed distance between the charges and their variable orientation relative to other dipoles (cf. Fig. 1). Such qualitatively different, higher order interactions determine emergent properties, such as a dipole moment.

3 From competition to synergy

3.1 Resource scarcity

While the above analysis provides a straightforward model for the spontaneous formation of systems with fixed, mechanical components, such as atoms, molecules or planets, the picture gets much more complex for *dissipative* systems [31,17]. Such systems must process matter and/or energy in order to maintain themselves, while dissipating entropy in the process. Most importantly, all living systems are dissipative, as they cannot survive without a continuing supply of food or energy. When mechanical components, such as molecules, interact, they may "compete" for features such as a minimal potential energy state, a particular position within an ordered arrangement, or closeness to a force field. But once the interaction has settled into a bond, the competition stops, and each component remains in or around its equilibrium state. Dissipative components, on the other hand, can never settle down into an equilibrium because they need an uninterrupted influx of resources.

Material or energetic resources are subject to *conservation laws*. This means that they cannot be created out of nothing; they can only be transferred from one system to another. The exchange of physical resources is a *zero-sum game,* where gains for the one entail equal losses for the other. In practice the game is rather negative-sum, since the second law of thermodynamics implies an irreversible loss of free energy through entropy increase. Therefore, components that need the same resources will by default be in a situation of *competition*.

While the available supply of any such resource is necessarily finite, the demands made by living systems are potentially infinite. This follows from a defining feature of life: growth and reproduction. According to Darwinian logic, the “struggle for life” is won by the living system that has the highest fitness, i.e. which is best at multiplying itself. Therefore any component that does not fully use the resources available to multiply itself will eventually be outcompeted by the one that does. Given that growth and reproduction are exponential processes, the consumption of resources tends to reach its ceiling (*carrying capacity* of the environment) very quickly, after which further growth is curtailed—until more resources somehow become available. This is the problem of *scarcity*: the demand for any physical resource used by a living system is almost always larger than the supply. Scarcity will create a selective pressure for any living system to maximally exploit the resources it has access to, thus thwarting the attempts of its competitors to consume these same resources.

3.2 Types of conflict and synergy

Competition for resources is a special case of *conflict*, the situation where different agents’ (explicit or implicit) goals are inconsistent, in the sense that success or progress for the one implies failure or regress for the other. We can distinguish two types of conflictual interactions: *symmetric* and *asymmetric*. In a symmetric interaction, both parties are affected to the same degree and gains and losses tend to be divided evenly. In an asymmetric one, the one party systematically gains more than the other. Pure resource competition is a symmetric conflict. Its asymmetric equivalent may be called *exploitation*. This is a relation in which one party (the exploiter) gets most of the benefits while the other party gets the losses. Special cases include predation, herbivory and parasitism, in which the predator, herbivore, or parasite directly consumes the resources used to build the body of the prey, plant, or host.

Interactions between living systems do not need to be conflictual, though. While the resources themselves are subject to a zero-sum constraint, *access* to resources is not. Living systems are only capable of gathering and processing a very limited amount of the matter and energy that exists in the universe, depending on properties such as location, metabolism, and knowledge. For any given system the amount of accessible resources is merely the minutest fraction of the total amount of potentially available resources. Improving access can turn a zero-sum interaction into a positive-sum one, that benefits both parties [39].

We will call such a mutually advantageous interaction *synergy*. In this case, the parties’ goals are consonant, and progress towards the one implies progress towards the other [14]. A simple example is collaborative hunting in lions, in which a pride of lions can kill much larger animals together than if hunting individually, thus increasing the range of prey to which they have access. When synergy is symmetric, meaning that it benefits both parties to a similar degree, we will call the interaction *cooperation*. When it is asymmetric, in the sense that one party derives benefit more systematically than the other, we may call it *cultivation*: the "cultivator" farms, breeds or cultures the other party in order to directly extract benefit from it, but at the same time indirectly helping it to prosper. Examples are farmers that grow crops, and ants that cultivate fungi or herd greenfly.

3.3 The free rider problem

In order to fully understand evolutionary transitions, we must note that scarcity, and therefore conflict, competition and exploitation, is the default situation. Synergy is the exception, as it requires a very specific type of interaction that somehow compensates for the inevitable dissipation of resources by simultaneously increasing access. This means that for dissipative systems it is a priori very difficult to find a state of fitting together, i.e. an interaction pattern that results in fitness benefits to all participating parties. For mechanical systems too, the initial state is competition, as when grains of sand "compete" to get as close as possible to the bottom of an hour-glass, but this competition stops as soon as the available resources (in this case space at the bottom) have been distributed, and the system has reached equilibrium. Dissipative and in particular living systems, on the other hand, are driven to maintain and increase their influx of resources, and therefore remain in a perpetual state of latent competition.

This means that even if a number of such components manage to find a mutually beneficial, fitting configuration, there will always remain a "temptation" to *defect* from the arrangement [7,14], i.e. to increase one's share at the detriment of the others. This is the problem of *free riders*: in any cooperative, variation of individual components will sooner or later create a variant that selfishly exploits the synergy generated by the others, meaning that it reaps benefits without investing any resources in return. Examples of free riders are tumor cells in the body, and thieves or cheats in society.

The fundamental problem is that this asymmetry of benefits allows the free rider to multiply faster than the others, so that its progeny eventually dominates the system—thus destroying the cooperative arrangement. The only way the cooperative can protect itself from extinction is by suppressing or controlling any moves towards defection. In both biological and social systems we find plenty of examples of such controls: e.g. the immune system, the police, and the judiciary. The fundamental issue in the modelling of evolutionary transitions then is how such sophisticated, adaptive control systems can evolve out of simple interactions.

3.4 Selection for synergy

While very few states are synergetic, and blind variation alone is very unlikely to produce them, such states have obvious fitness benefits. Therefore there will be a consistent *selective pressure* towards achieving them. We now must examine how rare such states really are, and whether the selective pressure will be sufficient to overcome the obstacles on the road to synergy.

The simplest interaction involves just two systems. For them to enter into a synergetic relation, their goals should be consonant. Competition can be avoided if the two systems require different resources, so that a gain for the one does not imply a loss for the other. This merely defines a relation of indifference, though, not one of cooperation [14]. Synergy can be achieved if the process of gaining resources by the one somehow, as a side effect, makes more resources accessible for the other. An example are lions leaving the for them unedible carcasses of prey for smaller scavengers, such as vultures and hyenas. This is still an asymmetric relation that does not bring benefit to the lions.

Full synergy is only achieved in a *mutualist* relation, where the benefits are reciprocated. For example, an anemone attached to the shell of a hermit crab gets better access to food because of the crab's movements, while the crab is better protected from predators by the anemone's tentacles. A more intense form of mutualism can be found in a lichen, a symbiotic association of algae and fungi, where the algae photosynthesize organic molecules and energy for the fungi, while the fungi collect minerals and water for the algae. Still, the interaction is not wholly symmetric, and some biologists consider the fungus to be a parasite rather than a mutualist, since the algae can survive without the fungi, but not vice versa. In the present terminology, the fungus is probably more of a cultivator than either an exploiter (parasite) or a cooperator (mutualist).

3.5 Similarity and complementarity

Generally, mutualism between two systems A and B is easiest if their resource use is *complementary*: i.e. A consumes what B produces, and vice versa. An example is the relation between animals, who consume oxygen and produce carbon dioxide as a waste product, and plants, which consume carbon dioxide and produce oxygen.

The same principle can be found in personal relations: psychologists studying interpersonal attraction find that people tend to like each other if they have similar attitudes ("birds of a feather flock together"), but somehow also if they complement each other ("opposites attract"). There is a simple solution to the riddle whether it is similarity or difference that is most attractive: the best relationships are based on similar (consonant) goals and values, but complementary resources or means for achieving those ends. The best person to collaborate with is one that will support you in achieving your objectives, by bringing in resources, such as talent, experience, or connections, that *you* don't have access to.

The reverse side of this principle is that synergy is more difficult to achieve when resource utilization is more similar. Greater similarity in utilization not only means less complementarity, but more competition for the resources that both parties need, and therefore more conflict. Mutualism is therefore easier to evolve for individuals of very different types (such as algae and fungi) than for individuals of the same species.

Since natural selection prefers a synergetic relation to a conflictual one, evolution will push systems to *differentiate* their use of resources over time. Competition between related species within the same environment (e.g. Darwin's finches on the Galapagos islands) will create a selective pressure for them to specialize in exploiting different niches, so as to have a minimal overlap in the resources they consume. The same dynamics can be found in the economy, where market forces push companies to differentiate their products from the ones of their competitors, so as to attract different clients.

Such ecological or economic differentiation can produce synergy as a side effect, since a variety of ways of processing resources (e.g. photosynthesis) will produce a variety of "by-products" (e.g. oxygen) which may become resources for a newly differentiated type of system (e.g. animals). However, the relations between any two components of such an ecosystem or market tend to be weak and opportunistic, with relatively little reciprocity or mutual dependence. There is no closure to tie the collective together, and without a control mechanism it is easy for outsiders or free riders to invade and exploit the system. Therefore, we will in general not view the evolution of an ecosystem or unregulated economy as a transition to a higher level individual. Typical higher level systems, such as multicellular organisms and societies, are formed through a different mechanism, which starts out with similar rather than differentiated components. To explain this, we need to examine the evolution of asymmetric relations.

3.6 From exploiter to cultivator

The selective pressure against conflict has a different effect on asymmetric relations. Asymmetry already implies a differentiation of niches or roles, separating the exploiter from the exploited. While the exploiter has the power to extract resources from the exploited without offering anything in return, such interaction is precarious in the long run. Success for the exploiter, in the sense of a growing harvest of resources, weakens the exploited, thus endangering the exploiter's future supply. Predators that are too successful may kill off their prey populations, and thus starve themselves to death. Parasites that weaken their host so much that it dies usually also get killed in the process. Even if no host actually dies, parasite variants whose hosts do better will win the competition from variants that weaken their hosts more. Therefore, evolutionists have long posited that parasites tend to lose their virulence, become more benign, and eventually evolve to mutualists, who fully compensate for the losses they inflict so as to keep their hosts thriving [7].

This principle is generally correct, although more recent theories have added some qualifications: 1) some parasites can infect new hosts even when their original host is very weak. For example, malaria is spread by mosquitoes biting sick patients. In that case, the selective pressure against virulence is limited [8]; 2) the dynamics of predator and prey populations, described by the well-known Lotka-Volterra equations, is characterized by negative feedback with a lag. This leads to limit cycles, as a decrease in predator populations allows the prey to increase in number again after a while, so that there is little danger of predators actually killing off all their prey. Still, in both cases predators or parasites that would manage to extract the same amount of resources at a lesser cost to the exploited would do better than their competitors, and thus a preference remains for less exploitative relations.

Thus, the general evolutionary tendency is for *exploiters to become cultivators*, i.e. to maintain their control over the systems whose resources they reap, but to become increasingly benign, thus ensuring that their "flock" thrives. For example, prehistoric humans, after killing off most of the large prey animals ("megafauna"), were forced to become herders, caring to maintain the health of their cattle. Warlords who came to dominate and exploit a group of farmers through sheer force first became feudal lords protecting their villagers against bandits, then more or less enlightened rulers, and eventually presidents, democratically elected for their assumed prowess in making the country prosper.

3.7 Application to evolutionary transitions

The emergence of cultivation can explain some of the most fundamental evolutionary transitions [28,35]. For example, eukaryotic cells are now assumed to have an endosymbiotic origin: the eukaryote's organelles were initially free-living prokaryotes that entered the larger cell as either parasites or prey, but that evolved into tightly integrated symbiotes "cultivated" by the eukaryote [26]. Even the origin of life itself may have followed this scenario: perhaps a self-replicating RNA molecule initially entered an autocatalytic cycle of reactions inside a primitive cell merely in order to exploit its products for its own replication, but then turned from a parasite into a cultivator, selectively suppressing or stimulating the different chemicals produced by the cycle or entering from the outside, in order to maximize its productivity and robustness.

The evolution of cultivators suggests a general solution to the free rider problem: the selective pressure to maximize the productivity of its “flock” without weakening it will turn the cultivator into a “manager”, in the terminology of Stewart [35], who controls conflicts and suppresses free riders that would otherwise sap the collective. This is easy to imagine when the cultivator is already a sophisticated agent, i.e. an organism with advanced capacities for control and cognition. For example, we may assume that a feudal lord or tribal chief already has the competence and inclination to punish cheaters and to adjudicate in conflicts between his subjects [39]. It is a little more difficult, but still plausible, to extend such a scenario to the case where the cultivator is a primitive cell such as a prokaryote, or even a complex molecule such as RNA.

But Stewart [35] extends this scenario even to “managers” that are non-material, such as religions, customs and institutions. Such social-informational systems can be seen as complexes of *memes*, i.e. ideas, traditions, rules, etc. that are transmitted from person to person, acting as the cultural equivalent of genes [2, 16]. Just like genes, memes can be selfish or parasitic [7,16], using their hosts merely for their own proliferation, without caring for the hosts’ well-being. Examples of such parasitic memes are certain religious cults [6], such as Heaven’s Gate or Aum Shinrikyo, that exploit or even kill off their followers. However, according to the rules of parasite ecology [8], vertically transmitted (i.e. from parent to offspring) parasites must lose their virulence, as their hosts must remain fit enough to produce sufficient offspring. Therefore, as Cullen [6] argues, the major world religions have evolved to a generally benign state. This means that they support the well-being of their flock, promoting cooperation and curbing internal conflict and profiteering through the imposition of well-honed moral rules [14].

We see that the parasite to cultivator/manager scenario, as proposed by Stewart [35], can explain a wide range of evolutionary transitions. However, it still provides little detail about how a new control structure precisely evolves, especially when the conceived “parasite” becomes increasingly abstract. To arrive at deeper understanding, we need to make one further generalization, turning the cultivator from an outside agent invading the collective into an internal, distributed mode of interaction that we will call “aspect”.

4 Aspect systems

When analysing the functioning of a system, our natural tendency is to first make a structural decomposition, i.e. to distinguish the spatially or materially separable components that we call *subsystems*. However, systems can also be distinguished on the basis of function, while being structurally inseparable. For example, within society we can distinguish economic, political and cultural systems, even though each is made up of the same individuals and artefacts, and occupies the same space. Such functional components may be called “aspects” of the overall system. An *aspect system* [37] can be defined as a subset of the set of relations, interactions and properties that characterize the structural components of a system which is restricted to a particular, coherent aspect of the system’s functioning.

For example, the state space $S = \{(x_1, y_1, x_2, y_2)\}$ of the two-component system in Fig. 1 can be decomposed as a Cartesian product of the state spaces of its subsystems:

$$S = S_1 \times S_2, \text{ with } S_1 = \{(x_1, y_1)\} \text{ and } S_2 = \{(x_2, y_2)\}.$$

However, it can also be decomposed into the state spaces of its aspect systems:

$$S = X \times Y,$$

where $X = \{(x_1, x_2)\}$ is the "horizontal aspect" and $Y = \{(y_1, y_2)\}$ is the "vertical aspect".

If we assume that all four dimensions, x_1, y_1, x_2, y_2, can vary independently, then the two decompositions are mathematically equivalent. It is only our physical intuition about objects being separate that would bias us to prefer the first decomposition over the second one. However, when the two subsystems have bonded, like in the right hand side of Fig. 1, the original variables are no longer independent. The only decomposition into independent degrees of freedom then is the one that distinguishes a "position aspect" $P = \{(x_m, y_m)\}$ and a "rotation aspect" $R = \{\alpha\}$:

$$S = P \times R$$

Subsystems and aspect systems are in a sense each other's dual, each representing distinct features of an encompassing system, but where the subsystems represent spatially localized features, whereas the aspect systems represent non-local or "distributed" features. For example, a wave can be decomposed either as a spatial pattern of amplitude changes (local), or, using Fourier analysis, as a superposition of sine waves of different frequencies (distributed). The wave's crests and troughs can be seen as subsystems, the sines as aspect systems.

Like subsystems, aspect systems can be more or less strongly *coupled*, in the sense that changes in the one covary to a lesser or greater extent with changes in the other. (Such covariation could for example be measured through the correlation coefficient for quantitative variables, and through conditional entropy or mutual information measures for qualitative variables.) A good decomposition of a complex system is one for which the postulated components—whether subsystems or aspect systems—are as independent as possible.

For example, changes in the culture, such as new styles of art, music or language, will have only indirect effects on the economy, and vice versa, even though both are important aspects of society. The reason is that these societal aspect systems represent different types of interaction: exchange of goods and services in the economic aspect, exchange of ideas in the cultural aspect. Of course, there still is a mutual influence, in the sense that new ideas may create a demand for a new type of goods, while the supply of certain goods may make society more receptive for certain ideas on how to use them. It is because of this indirect dependence that culture and economy cannot be fully disentangled, and are best modelled as aspects of the encompassing system of society.

The fact that aspect systems can be relatively independent even when the subsystems are not, offers us a new perspective on the dynamics of self-organization [9]. Most importantly, aspect systems may co-evolve without competition, as the "resources" they require can be wholly different. For example, in order to survive and develop the economic aspect needs material transactions as resource, while the cultural aspect needs informational exchanges. There is some overlap in the resource consumption, since an economic exchange still requires some information exchange (e.g. about the features of the product one is buying), while a cultural interaction may still require a material carrier (e.g. books as vehicles of ideas). In that respect the two aspects will to some degree compete, but the bulk of the investment in each case goes to a different resource. For example, you don't need to be wealthy to be an influential thinker or artist, and you don’t need to be very cultured in order to make money producing soft drinks.

In conclusion, aspect systems provide us with a new conceptual tool to analyse the emergence of cooperation in a collective of initially competing subsystems.

5 From medium to manager

5.1 Collective and medium

Let us consider a single aspect system of a system that consists of similar, and therefore competing, agents. This aspect system represents the possible interactions between the agents. In general, there exist different types of interactions—such as economic and cultural, or electromagnetic, nuclear and gravitational—that are best represented as different aspects. Yet, for simplicity we will start by lumping all interactions together. The aspect system can then be seen more concretely as a *medium*, i.e. an abstract support for carrying interactions, communications, or exchanges between the agents that it connects. For example, if the interactions are linguistic, the medium is the language shared by the agents; if they are electromagnetic the medium is the electromagnetic force field between charged particles.

Note that under this assumption the medium does not exist independently of the agents that use it: no language without language users, no electromagnetic force without charged particles. The medium is truly an aspect—not a physically separable subsystem—of the system of agents. The medium’s fundamental resource, which it needs to maintain and develop, consists of the agent’s activities.

If we ignore the inter-agent relations, the collection of all agents also defines an aspect of the overall system, but one that only includes aggregate properties, such as total input and output of resources, or number of components. We will call this primary aspect system the *collective*. Conceptually, the medium and the collective occupy different levels in the dynamical hierarchy: the collective comprises the properties that are merely the “sum” of the properties of the components, while the medium is made up of the emerging properties, that do not exist at the level of the individual components. In the previous example (Fig. 1), the position aspect, being the average (sum) of individual positions, can be viewed as collective, the rotation aspect as medium.

5.2 From medium to mediator

The resources required by the collective—the “food” and “energy” needed to keep the individual agents alive—are essentially different from those required by the medium. This means that medium and collective are not in direct competition, and therefore well-positioned to evolve synergy. Their interaction is asymmetric, though, as we might say that *the medium exploits the collective*, in the sense that it draws its strength from the collective’s activity, initially without giving anything in return. In the terminology of Haken’s synergetics [11], the interaction mode “enslaves” the components.

However, we have seen that exploiters tend to evolve to cultivators. While the initial selective pressure is for the medium to make the agents more active in their interactions, this may “exhaust” the agents’ resource level, and therefore eventually weaken the medium. Thus, the longer term selection will be for the medium to become more supportive, helping the agents to conserve—or increase access to—their resources. The most direct way to achieve this is by suppressing the conflicts that normally arise between similar agents and that sap their resources, by mediating and coordinating the agents’ actions. Thus, the medium becomes a conflict *mediator* [30].

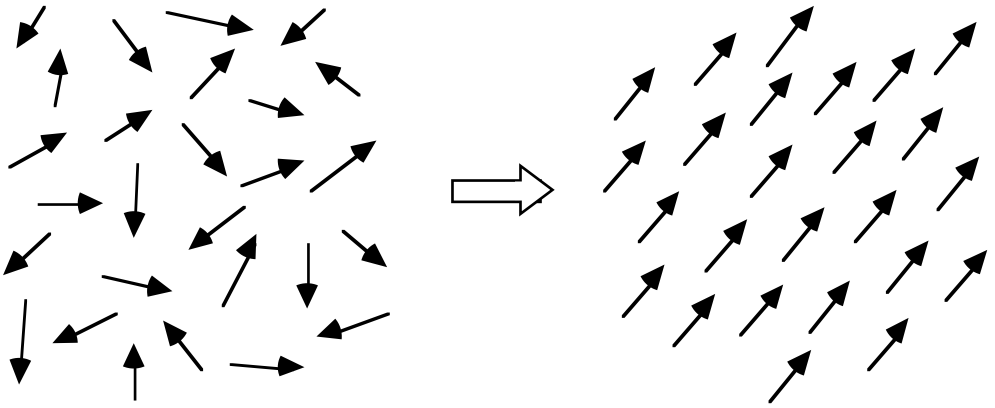

Figure 4: self-organization of spins, from random and conflicting (left) to aligned and synergetic (right)

Let us illustrate this process using a classic example of self-organization [22,11]: magnetization. A potentially magnetic material consists of a collective of identical atoms or molecules (spins), each with its own magnetic field, initially pointing in a random direction. The spins interact through the forces of attraction between opposite magnetic poles and repulsion between similar poles. The global magnetic field is the medium carrying these interactions. Because of repulsion, neighboring spins cannot point towards each other, and therefore there is conflict. Initially, because of thermal fluctuations spins will vary more or less randomly with respect to their neighbors. Sooner or later, this variation leads to a couple of neighboring spins aligning in the same direction, thus minimizing conflict. This strengthens the local magnetic field that now exerts a pressure on farther away spins to align in that direction as well. The more spins point in the same direction, the stronger the field becomes, and the more spins are inclined to join the alignment. Eventually, all spins point in the same direction, maximizing the overall field (Fig. 4). In our previous terminology, the initially weak and disorganized medium has evolved to a state of maximum fitness by mediating the conflict between the components of the collective, constraining them to a coordinated, organized state of full synergy (the “slaving” principle, according to Haken [11]).

5.3 Spatial partitioning

All spins aligned in the same direction is an “ideal” case. A suboptimal, but perhaps more realistic, alternative is that distant regions would align themselves differently, so that most spins would be parallel to their neighbors, except for those on the borders of a region. This is effectively a spatial *partitioning* of the collective in subsystems or regions that are internally synergetic but mutually in conflict.

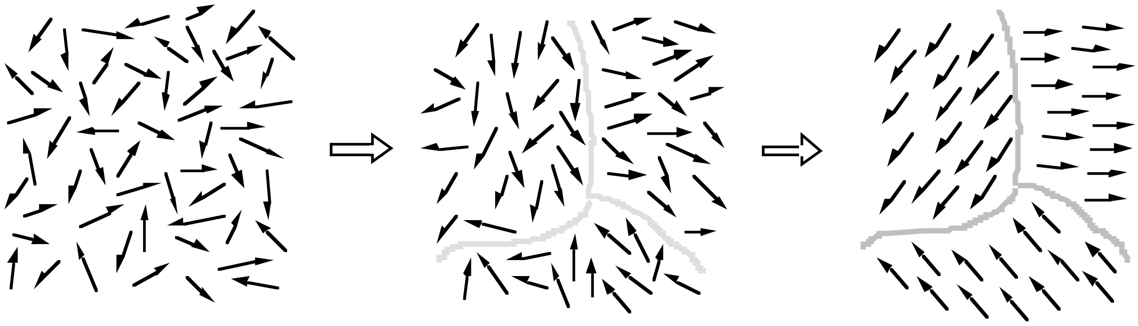

Figure 4b: spatial partitioning of spins, from random and conflicting (left) via partially coordinated to partioned in 3 separate, internally aligned regions (right)

This type of situation is common in biology, where a population of animals of the same species is typically partitioned in geographically separate groups or subpopulations. In that case, natural selection at the group level will promote cooperative behavior *within* the group, but competition *between* groups [14]. However, cooperative groups are vulnerable to invasion by free riders [7]. As confirmed by the simulations of Lenaerts [25], the probability of cooperation being destroyed in this way increases with the diversity within the group and the ease with which individuals can switch groups. Cooperation is most robust when spatial partitioning is strongest, i.e. when the groups are homogeneous and do not exchange agents. This is another rudimentary example of mediator evolution, in the sense that interaction patterns that maximize consistency of goals within the group (e.g. genetic relatedness, "groupthink", ostracism of non-conforming individuals), and separation between groups (hostility towards outsiders) become self-reinforcing, increasing the synergy and thus the fitness of the overall system.

This trick of physically separating potential competitors in order to avoid conflict has evolved many times in the history of life. Another classic example is the separation between reproductive (germ-line) and non-reproductive (somatic) agents in multicellular organisms and in insect societies [28,29]. Similarly, destructive competition between different strains of mitochondria is avoided by only allowing the mitochondria of the mother to be passed on during sexual reproduction [28,35].

5.4 Dynamic coordination

In the previous examples the resulting spatial organization is static and rigid. Mediators, however, can also regulate on-going dynamics, as we will illustrate with the example of Bénard convection.

When a liquid is heated from below, the lower layers expand and become lighter than the upper layers. This creates a conflict, as the lighter liquid tries to flow upwards, while in the same space the heavier liquid tries to sink to the bottom. At the molecular level, individual components move in a random direction until they collide with another molecule. These scattered movements form the medium, which initially is wholly disorganized. However, if in one spot a few more bottom molecules are moving upward, this upward motion will be reinforced by the temperature difference, creating a drag on neighboring molecules to adjust their direction of movement upward as well. The departure of molecules from the bottom layer creates a lower pressure region where other molecules can now move in, thus creating a downward flow a little further, which gets similarly reinforced. Upward and downward flows grow stronger and more differentiated, eventually dividing the available space between them so as to eliminate conflict. Thus, the liquid organizes itself in a regular pattern of rotational flows or "Bénard rolls" (see Fig. 5).

In the present terminology, internal variation (random interactions between liquid molecules) has led the aspect system to adapt to the selective pressure (warm liquid needing to move up, cold liquid down). Thus, this classic example of distributed self-organization, used to illustrate the emergence of synergetic or cooperative behavior, can be conceptualized as an evolution from a medium to a mediator, coordinating the collective from which it emerges.

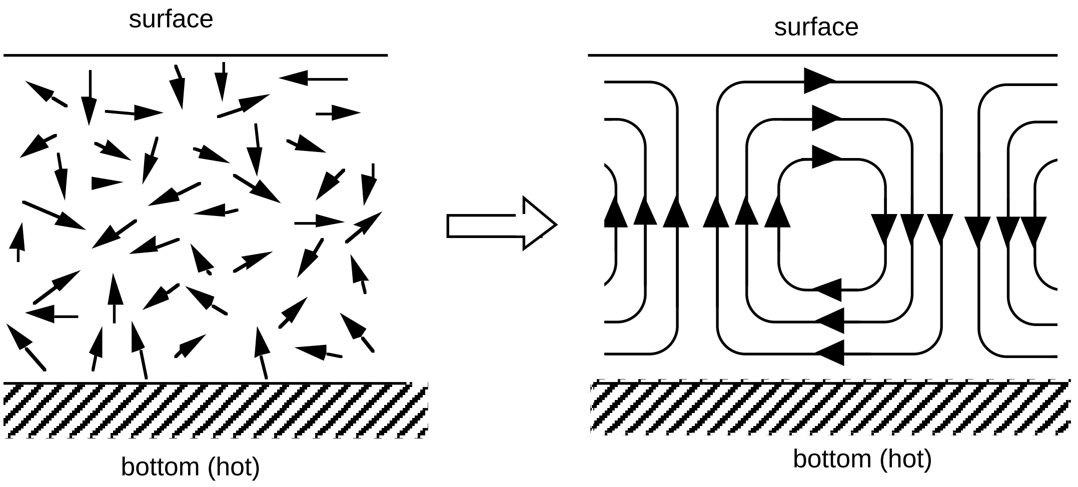

Figure 5: self-organization of movement in a liquid: from random and conflictual (left) to the coordinated and synergetic form of Bénard rolls (right).

This physical example is readily generalized to biological and social systems. Moving agents, such as animals or vehicles, compete for the space they share. For example, two drivers wanting to cross the same narrow bridge are in a state of conflict: only one can go first, the other one must give way. Like the molecules, freely interacting agents will evolve a system of interaction rules that minimizes conflict and obstruction. For example, a convention may arise that agents coming from opposite directions on a narrow road remain on opposites sides (e.g. righthand) of the road so as not to get in each other's way, and that agents moving in the same direction remain at a minimum distance from each other, like in swarms. This can again be viewed as an interaction medium evolving to become a mediator.

5.5 Co-opting external support

Up to now, we have viewed the mediator as a pure aspect of the system constituted by the agents. However, if this is in its fitness interest, the mediator, being relatively autonomous, may annex, co-opt or take over components that are not part of the initial agent system. For example, a "traffic regulating" rule system may extend itself to exploit part of the physical environment so as to assist the agents' movements. A simple example of this are the paths created by the frequent movement of animals through a forest or other irregular terrain. The network of paths not only physically facilitates, but informationally guides and regulates, the motion.

The erosion of a path in dense undergrowth could be seen as merely a side effect of the agents' movements. However, the mediator can incite the agents to actively produce an external support for its coordinating function. This is called *stigmergy*: part of the environment is used as a registry of signals that help coordinate the agents' actions [36,20]. The classic example are the trails of pheromones that ants leave on their way between different foraging sites, that will guide other ants in deciding where to go for food. The same principle underlies the variety of signs, road markings and traffic lights that have evolved to regulate traffic. For example, the lines separating lanes, the stop signs, and the arrows indicating obligatory directions all reduce the probability of obstruction, thus making vehicle movement more efficient and less dangerous, i.e. more synergetic.

Note that such inside-outside extension can also go the other way around, as when an external exploiter (e.g. a parasite or a warlord), evolving into a cultivator, co-opts internal mechanisms (e.g. metabolic processes or existing cooperation patterns) to better mediate conflicts.

5.6 Emergence of control

We have seen how the evolution from medium to mediator increases synergy and reduces conflict by carefully dividing and coordinating the actions of the agents in the collective, using external support if needed. The next step to increase synergy is the evolution of a *manager*, i.e. an aspect system that not only passively mediates the spontaneous actions of the agents, but actively initiates and controls such actions in order to benefit the collective. This is necessary in particular for the collective to overcome dangers and exploit opportunities in the environment that are too large or too complex for an individual agent to cope with. Note that while for simplicity we distinguish the subsequent stages of (1) medium, (2) mediator and (3) manager, in practice the development of coordinating systems will be more or less continuous, generating a variety of hybrid or intermediate cases that in some respects function more like a medium, in others like a mediator or manager.

A manager can be seen as a regulator or control system in the cybernetic sense [13], i.e. a system that tries to achieve certain goals or values (which are internal representations of the preferred or fitter states of the system), by performing actions that compensate for any perceived deviation from those preferred states. Deviations may be caused by internal or external perturbations (e.g. attacks by predators or parasites), or simply by the lack of the resources or conditions necessary to attain the preferred state (e.g. hunger or cold). The minimum architecture for a control system is a *negative feedback* loop with *amplification* and a *reference signal* [32]. Negative feedback assures that deviations are reduced, amplification that the counteractions are energetic or powerful enough to keep deviation low at all times, and to achieve or maintain a goal state that is not in itself an equilibrium state. The reference signal represents the goal to be achieved, so that, whatever the size and direction of the deviation, the system can compare the present state with the desired state, and decide about the appropriate counteraction.

A simple way to achieve negative feedback with amplification is to start from a positive feedback (e.g. autocatalytic) cycle, which by definition amplifies any change, but have it depend on one scarce “reference” resource, so that it can never grow beyond the value of that resource. In that case, deviations from the reference value will be automatically corrected—upward by autocatalytic growth, downward by exhaustion of the scarce resource. For example, if population growth depends on a stable, sustained supply of food in the environment, population will grow up to the carrying capacity, but any overshoot will quickly lead to a downward correction, resulting in a relatively stable population. In Bénard convection, the initial movement of liquid is amplified by the energy provided by the temperature gradient, but once the roll has formed, its velocity will stabilize depending on the precise amount of heating from below. Heat and food in these examples function as external reference signals.

An autonomous control system, however, needs to have an internal reference that represents the optimal configuration for survival and growth rather than the contingent value of some environmental parameter. Otherwise, the system may be destroyed by some fluctuation in that parameter (e.g. food running out, or the heating being switched off or increasing to the boiling point). RNA can be seen to play that role in the metabolic cycle of a cell. RNA is an essential, but scarce, resource, which is necessary to catalyse the basic chemical reactions. Therefore, the amount of RNA released by the genome determines the presence and speed of chemical reactions in the cell, thus controlling the metabolic activity.

We have suggested earlier that RNA may initially have been an external parasite that entered and exploited an autocatalytic cycle. However, RNA may also have appeared as an internal byproduct of the cycle that somehow was helpful in regulating the cycle's further activity, or as an external resource that was co-opted by the cycle to help it function more reliably. In the present functional analysis, the internal or external origin of a reference signal is not fundamental. The important issue is how the mediator has evolved more reliable regulation by developing reference signals that vicariously represent [3] the fittest state for the system.

5.7 Mediator evolution in economics

An economic example may further illustrate the generality of the proposed scenario for evolutionary transitions: collective → medium → mediator → manager.

While exchange of resources (e.g. fruit for meat) within a collective has obvious synergy benefits, it is a priori difficult to find the right partners (i.e. who possess complementary resources) to engage in a mutually advantageous transaction. This becomes easier with the emergence of a *market*, i.e. a medium for direct interaction between all the agents, where a given agent can meet many potential partners before choosing the most fitting one. Still, it is unlikely that any two agents would each possess just the right type and amount of resources to precisely fulfill the other's demand.

This problem was solved by the evolution of a single reference resource that could function as mediator between the different demands [40]: *money*. The functional equivalent of money has evolved independently in different historic civilisations [39]. In some cases, one of the resources that had already a central role in the system of transactions (e.g. wheat or salt) took on an even more general, reference role, becoming exchangeable for any other resource. In other cases, a peripheral, but scarce, resource, such as gold or sea-shells, was co-opted to play this central role. In yet another case, a functional or aspect system (e.g. an IOU agreement) evolved a physical embodiment (e.g. a cheque, bond or bank note) that could play the role of reference resource.

Once money had evolved, a new property could emerge to support a reference signal: the *price*, i.e. the monetary value—or equivalent in money units—of any given resource. In the present market mechanism the price functions as an error signal, representing the deviation between the ideally desired availability of resources (collective *demand*) and the actual availability (collective *supply*) [18]. The price is zero only if there is no scarcity, i.e. if the supply is always larger than or equal to the full demand. The larger the price (error), the higher the motivation for agents to possess and sell that kind of good, and therefore the more effort they will invest into increasing the supply, thus reducing the deviation between supply and demand. The price mechanism turns the market into a negative feedback loop with amplification (because a small change in price can lead to a large change in production effort) and a reference signal or goal (optimal satisfaction of the demand).

Thus, the "invisible hand" of the market is actually a distributed control system [18] or *manager* emerging from the mediator that is money and the medium that is the market-place. This manager coordinates, regulates and initiates interactions between the agents of the collective so as to—theoretically—maximize their synergy.

Note that in practice markets are far from the optimizing systems envisioned by neo-classical economists, which is why additional regulators such as institutions, taxes and subsidies had (and still have) to evolve. This is due in part to the fact that as yet the "demand" signal does not reliably represent the true needs of the collective, as it is subject to vicious cycles such as the poverty trap, technological lock-in, and the booms and busts caused by speculation [18], and to the continuing threat of free riders, which must be held in check by mutual monitoring and legal control [14].

5.8 Distributed cognition

Perhaps a last step in the development of the manager is the evolution of *distributed cognition* [23]. Control entails knowledge, since the control system must *know* which action to perform in order to correct which deviation [13, 27]. When deviations can be represented by a one-dimensional variable, such as temperature or price, this may appear trivial. The only "knowledge" needed in this case is the direction in which to compensate—e.g. heat when it is too cold, cool when it is too hot. The control loop ensures that this will drive and maintain the system near its reference point. In more complex, multidimensional state spaces, however, choosing the correct sequence of actions to achieve the goal is everything but trivial, and the control system must incorporate a *model* of the problem environment in order to achieve any success rate better than chance [5].

This model will be implicit in the pattern of interactions defining the mediator/manager. For example, an efficient market implicitly "knows" which combination of goods and services to produce in order to satisfy present and anticipated demand [18], and uses a variety of interaction channels between investors, suppliers, producers, sellers and buyers to propagate the right information to the right agent. The manager may also use an external support to store and disseminate its knowledge among the agents. For example, the pheromone network produced by ants can be seen as a distributed model or mental map [20] of their foraging environment, which is available for consultation by any agent.

5.9 Organizational closure

Another innovation brought in by the emergence of a manager is organizational closure [27]. A control system by definition distinguishes phenomena that perturb its desired functioning from those that do not. The disturbances are interpreted as trouble-makers that must be blocked, neutralized or expelled, whether their origin is internal (e.g. waste, functioning errors or free riders such as tumor cells) or external (e.g. temperature changes or parasites). Thus, an effective manager will protect the system by closing it off from unwanted interactions, thus maintaining a strict separation between "self" (contributing to its survival and growth) and "other" (endangering survival and growth). The classic example of such a manager is the immune system, which learns to distinguish between "good" (self) and "bad" (other) molecules, attacking the latter while leaving the former in peace. Note that this closure is organizational or functional—not topological—since "bad" may originate internally (e.g. tumors) and "good" externally (e.g. food or co-opted parts of the environment, such as tools).

6 Conclusion

We have seen that variation and natural selection automatically tend to create higher order systems out of independent components, by the selective retention of stable assemblies [19]. The recursive emergence of such assemblies produces a dynamical hierarchy.

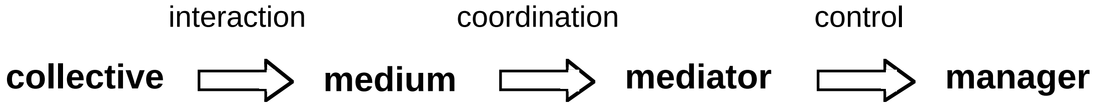

Fig. 6: summary of the proposed scenario for an evolutionary transition. The arrows connect subsequent stages of the emerging higher level system, and are labeled with the processes that produce them: 1) a collective of agents begins interacting, thus constituting a medium; 2) the medium self-organizes so as to better coordinate the interactions, becoming a mediator; 3) the mediator establishes active control over the agents, becoming a manager.

However, when the components are dissipative systems, that must remain far-from-equilibrium, the problem is to maintain such an assembly in the face of on-going competition for scarce resources. While at the higher level there is a selective pressure for finding synergetic configurations that minimize conflict, at the lower level there always remains a "temptation" to defect from such an arrangement, leading to the creation of free-riders that eventually undermine the synergy. The precariousness of such symmetric forms of synergy (cooperation) can be counterbalanced by the evolution of asymmetric relations. In this situation, the selective pressure for synergy makes exploiters evolve into cultivators. The control exerted by the cultivator over the cultivated gives the latter the power and the "motivation" to suppress conflict in the former.

While intuitively we tend to see the exploiter or cultivator as a separate agent (e.g. predator or parasite) taking control of the system from the outside, this scenario applies equally well to the internal, distributed modes of interaction that we have called "aspect systems". Every collection of interacting agents has an aspect system that is simply the medium carrying the interactions. While this medium initially exploits the agents' activity to survive and grow, selection will make it evolve it into a cultivator that improves the collective fitness of the agents by attenuating conflict and promoting synergy. We have called the next stage of this evolution the "mediator" (see Fig. 6). A mediator reduces obstruction, waste of resources, and risk of conflict or cheating, and increases complementarity and mutualism by constraining or directing the agents' autonomous actions so as to achieve the best possible coordination. In the final stage, which we called "manager", the mediator intervenes actively to make agents perform the precise actions that most benefit the collective, as represented by the reference signal or goal of a control loop. This completes a full *metasystem transition*, i.e. the evolutionary emergence of a higher level of control [38, 17], regulating the activities of the components below and integrating them into a new "individual" or "self".

Although several authors [29, 28, 38, 17, 21] have discussed a series of examples of such a transition, none seems to have proposed a general scenario for its dynamics—one that is applicable to a broad variety of cases, while being sufficiently concrete to allow a step-by-step analysis of the different aspects and functions that need to evolve. While the present paper cannot go into details about any specific transition, one more example may illustrate the generality of the present scenario.

An important mode of interaction between cells is for one cell to release a chemical that is absorbed by another cell. The various chemicals diffusing through the shared space form a medium for the collective. This can evolve to a signalling device or mediator to coordinate activities, like in certain bacterial colonies where the presence of a poison triggers the bacteria that come into contact with it to broadcast a “danger” signal that warns other cells to move away from it. Initially all cells are able to emit and respond to the same signals, but during the development of a multicellular organism such signals entice cells in different locations to differentiate into different tissue types (spatial partitioning), which now broadcast and react to signals differentially. Such chemical broadcasts are called “hormones”. The hormonal system is a true metabolic control system, distributed over the whole organism, which coordinates and exerts power over the cells’ crucial activities—even going so far as to make individual cells commit suicide (apoptosis) when this is to the fitness benefit of the collective.

Another important difference between the present approach and earlier ones, is that evolutionary transitions are usually seen to occur sequentially, e.g. prokaryotes → eukaryotes → multicellular organisms → societies. However, the mediator scenario allows different transitions to occur in parallel, each supported by its own interaction medium (or outside exploiter). For example hormonal and immune systems evolved simultaneously, as did economic and political systems. While mediators can be largely autonomous, they will always interact to some degree, possibly reinforcing each others’ synergy-promoting effects. The picture is further complicated by the fact that mediators can co-opt various external supports that may or may not interact with other mediators. This allows for a very rich and subtle dynamics and the development of the complex and flexible organization that we find in real organisms and societies.

Yet, the principle that aspect systems can be defined so as to be as independent as possible gives us the hope that the essential steps in this process can still be analysed, modelled and understood—possibly with the help of simulations. Perhaps the most important lesson from the mediator scenario is that realistic formalizations of a metasystem transition will have to go beyond our reductionist intuition, which tends to decompose a system into structural components or *subsystems*, rather than distributed interaction patterns or *aspect systems*. Mathematically, it would seem that aspect system modelling is not intrinsically more difficult than subsystem modelling. Practically, the main issue for future research will be to get the best possible decomposition.

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