The Multidisciplinary Patterns of Interaction from Sciences to Computer Science

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> *We have to study the interactions as well as the parts.*
> John H. Holland, "Emergence: From Chaos to Order" [23, page 14]

Summary. Interaction is a fundamental dimension for modelling and engineering complex computational systems. More generally, interaction is a critical issue in the understanding of complex systems of any sort: as such, it has emerged in several well-established scientific areas other than computer science, like biology, physics, social and organizational sciences.

In this chapter, we take a multidisciplinary view of interaction by drawing parallels between researches outside and within computer science. We point out some of the basic patterns of interaction as they emerge from a number of heterogeneous research fields, and show how they can be brought to computer science and provide new insights on the issue of interaction in complex computational systems.

1 The Many Facets of Interaction

Interaction is a fundamental dimension for modelling and engineering complex computational systems. In particular, in a world where software systems are made of an ever-increasing amount of objects, components, processes, or agents, and where the Internet, with billions of interacting clients and servers, represents the most widespread application environment, it is quite apparent that interaction is today the most relevant source of complexity for software systems of any sort.

Obviously, complexity is not a peculiar feature of software systems: instead, the notion of complex system crosses the strict boundaries between different scientific disciplines, ranging from physics to biology, from economics to sociology and organization sciences. Rather than making complexity a hazy and fuzzy concept, such a multidisciplinary interest has produced a flow of innovative and stimulating research that has started debating and penetrating the intricacies of complexity as a whole, trans-disciplinary concept. Starting from the pioneering work of Simon [44] on complex artificial systems (whose acceptation of complexity and complex system is the one implicitly adopted here), this has led to the recognition that there exist some "laws of complexity" that characterize any complex system, independently of its specific nature [26]. No matter if we are modelling the behaviour of a human organization, the life of an intricate ecosystem, or the dynamics of a huge market-place, we can expect to find some repeated patterns, some shared schema, some common laws that makes all these systems look similar when observed at the right level of abstraction.

Analogously, when we focus on artificial, computer-based systems, exploiting a multidisciplinary approach in order to understand complex software systems comes to be almost mandatory, rather than useful or merely inspiring. This holds, also and in particular, when trying to fully understand the role of interaction within complex software systems. In this perspective, we argue that one should first look at the many scientific research fields dealing with complex systems of any sort, and devise out the multifaceted aspects of interaction they exhibit. Along this line, in this chapter we liberally draw from the findings of some relevant fields dealing with complex systems, and try to outline the many diverse patterns of interaction as they independently emerge from such a wide range of different research fields. Then, we discuss how results coming from such heterogeneous sources can be used to draw some fundamental conclusions about the nature and role of interaction within complex software systems. Whenever the sake of clarity demands it, we focus on multiagent systems (MAS), as they encompass the widest range of sources of complexity (intelligence, autonomy, mobility, decentralised control, etc.) among the modern software paradigms.

First of all, Sect. 2 introduces a suggestive view on interaction as it comes from the world of physics. There, the issue of interaction has slowly emerged as a relevant one—from Newton's reflections on mediators of forces, to the N-body problem—to become a key one in the last century, when physicists focused on the one hand on devising out the mediator particles for fundamental forces, on the other hand on defining the general theory encompassing all known fundamental laws that govern interaction between basic particles. Then, according to the view currently promoted by the most advanced research, all physical processes could possibly be explained in terms of the *interactions* among vibrating filaments of energy, called *strings* [19]. So, even at the most fundamental level of human science—the world of fundamental physics—it is interaction that works as both the source of complexity and the potential source of solutions. Even though the above point may be argued (and with some reasons) to be more speculative than scientifically well-founded, it seems at least indicative of the fact that dealing with complex systems first of all means understanding and modelling the patterns of interaction among the basic system components.

The distinction between the "replicator" and "interactor" units of selection that has characterized a good deal of the last decades' discussions in the field of evolutionary biology is also quite revelatory [25], as discussed in Sect. 3. Roughly speaking, the scientific debate has led to a recognition that causality of natural selection (and thus, evolution of biological systems) resides in the entities that interact with their environment and make replication differential (interactors), rather than in the individual entities that pass on their structure in replication (replicators) [17]. Then, it is not merely that complex systems demand that investigations focus on interaction. By taking biological systems as meaningful examples of complex systems, we see that their evolution over time cannot be understood except in terms of the interactions of their individual components with the environment. This agrees with the Brooks' revolution in robotics [5], where interaction with the environment is proposed as the main source for intelligent behaviour of artificial systems, as well as with recent trends of computational research such as agent-oriented software engineering [3], which promote the *environment* as a first-class entity in the engineering of situated computational systems [34]. More generally, this says that the interaction between components of whichever sort and their environment is a fundamental dimension for modelling and engineering complex software systems.

Biological systems tell us something else about the nature of the interaction with the environment. By taking into account the well-studied behaviour of ant colonies [18], it is quite easy to see how some key features of complex systems—such as emergent behaviours, some forms of global intelligence, and system self-adaptation to changing environment conditions—can stem from stigmergic coordination, that is, the result of interactions occurring among individuals (ants) *through* the environment (through pheromones, in the case of ants) [21, 24]. Such sorts of complex systems, in short, exhibit independent and autonomous individual components, that interact with each other mainly by modifying the surrounding environment, through *mediators* (e.g., the pheromones) that physically embody an information content, and whose characteristics (e.g., the rate of decay) affect the nature of interaction among components, as well as the global behaviour of the system and its evolution over time.

Mediated interaction, the nature of the mediators, and their intrinsic influence over the global system behaviour, emerge as key issues for understanding complex systems—and, quite possibly, for modelling and engineering computational systems. Given the social nature of biological systems like ant colonies or hives, it does not come as a surprise that mediated interaction and the related issues are addressed in even more detail in the context of psychological and organizational sciences. Accordingly, in Sect. 4 we show how activity theory (AT) [29, 49] provides a promising framework for understanding the nature of interaction in complex systems seen as organizations. Central to AT is the notion of *artifact*, which serves as a *mediator* for any sort of interaction in human activities. Artifacts can be either physical, such as pens, walls and traffic lights, or cognitive, such as operating procedures, heuristics, scripts, individual and collective experiences, and languages. As mediating tools, artifacts have both an *enabling* and a *constraining* function, in that they expand the ability of the individuals to interact and affect the environment, but at the same time, as the vehicles for interaction, they limit this ability according to their own nature and structure.[1] The findings of AT can be recast in terms of computer science, by implicitly interpreting complex software systems as complex organizations. In order to make the system work and dynamically adapt to the changes of the world where it functions, mediating artifacts should exhibit properties such as malleability, controllability, predictability and inspectability. These features would allow and in principle promote dynamic adaptability of systems, intelligent self-organization, and support individual intelligence [36].

In Sect. 5 we draw from recent anthropological studies on the history of human societies to suggest how mediating artifacts should be reified within complex software systems. There, it has been shown that when the size of a human society grows over a certain number, direct interaction and sharing of power among peers is not functional any longer, threatening the survival of the society [11]. In response to such a growth in scale, that makes social systems unmanageable and unsuccessful in the long term, social *institutions* are always created (political and religious hierarchies, armies, administrative structures) which typically take the form of social *infrastructures*, that embody social laws and norms, and regulate the life of the societies. In term of computer-based systems, this corresponds to the recent trend toward *governing* infrastructures [35] which make it possible to govern the complexity of software systems by harnessing their interactions. This is illustrated by the notions of coordination service [48] and of e-institution [33] among others.

2 Interaction as a Fundamental Dimension of Systems

2.1 Interaction in Physics

Research in physics explores the nature and dynamics of the most complex system we can experience and observe: our physical world. By adopting a birds-eye view over the history of physics (that most physicists would probably execrate, but that may fit our needs as computational scientists, here), it is quite interesting to see how the issue of interaction developed here.

From Democritus to Mendeleev's periodic table, the first two thousand years of research on physics (in its most general form, thus including physical chemistry and the related disciplines) has been dominated by the interest in the nature and properties of fundamental "atomic" particles, the microscopic bricks of matter from which the macroscopic structure and dynamics of the whole Universe could be inferred. However, Newton's mechanics revolution

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[1] As a simple example, a spear-thrower extends the reach of a hunter's arm, but also prevents him having both hands free.

positioned the problem of interaction as a core concern, perhaps for the first time. Each individual physical entity of a system does not simply behave according to some intrinsic properties, but continuously interacts with other individual entities in the system, so that the cumulative effects of all the interactions determine the global system behaviour.

Despite the simplicity of Newton's laws, the three-body problem (and its N-body generalisation[2]) already suggested how much complexity can emerge from interaction. However, it was Newton's philosophical reasoning that led to the first speculations about the nature of interaction between physical bodies, and about the existence of *mediators* enacting forces working between distant bodies as a form of implicit "communication". This inspired vision resulted in the attempt to encompass the whole spectrum of the fundamental forces of Nature within a single general framework, along the two directions of quanto-mechanics (at the microlevel) and Einstein's general relativity theory (at the macrolevel). Along this line, physicists strongly focused on the interaction issue: on the one hand, they tried to devise out and observe specific mediator particles for every known fundamental force, on the other hand they aimed at defining a unifying Theory of the Whole that could account for all the known fundamental laws of interaction.

The conflict between quantum-mechanics and relativity views may be resolved by the theory of strings, which not by chance introduces a suggestive view of interaction as a first-class issue in the world of fundamental physics [20]. According to string theorists, the whole universe is made of elementary particles, called strings, which are filaments of energy that have a spatial extension (they are not zero-sized particles) and vibrate. Their shape, and the various ways in which they can vibrate determine their observable properties, and produce (and explain) the huge variety of particles that fundamental physics has discovered or conjectured in the last centuries—in particular, mediators like gluons and gravitons. Also, the fact that strings are dimensional particles makes their mutual interaction an event that is nonatomic in space and time. The modalities of interaction among vibrating strings seem so complex that the conceptual and practical tools available to physicists today often fail to satisfactorily model the resulting physical processes.

What concerns us here, is one of the fundamental assumptions of string theory: that is, that all physical processes can be explained in terms of interactions among vibrating strings [19]. As a result, it is no longer possible to explain phenomena in the physical world in terms of the individual behaviour and properties of individual entities (e.g., their position and speed), which are then put together according to quite simple interaction patterns/laws—as in the case of classical Newtonian mechanics. Instead, the world of strings look rather like a place where complexity is largely a result of articulated interac-

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[2] The well-known N-body problem can be formulated as follows: given N bodies, their initial positions, masses, and velocities, finding their subsequent motions as determined by classical, Newtonian mechanics.

tion patterns between the individual components. So, even at the most fundamental level of human science—the world of fundamental physics—interaction (among strings, at the current state of knowledge) works as both a source of complexity and a potential source of solutions.

2.2 Interaction in Computational Systems

The trend toward interaction in physics research has been parallelled in computational sciences, in particular by the intuitions of Robin Milner [31] and by the remarkable work by Peter Wegner [50, 51]. One of the starting points of Wegner's work was the incoherent situation of computer science as it emerged at the end the 1980s: a world where algorithms and Turing machines dominated the theoretical scene, while computers everywhere were operating under a completely different computational paradigm, yet to be even recognized. In short, Wegner argued that Turing machines actually expressed only the scale of complexity of algorithms as executed by sequential machines with no interaction whatsoever, apart from initial input and final output. At the same time, practical experience with any computer featuring an even trivial operating system provided evidence of an interactive way to compute that was not accounted for in any way by Turing's model.

The resulting claim, with formal support recently added to the already quite convincing evidence [16], was that computation should be conceived as spreading over two orthogonal dimensions—*algorithmic* and *interactive* computation—that give rise to different levels in the expressiveness of computational systems. While Turing machines were perfect models for algorithmic computation, they could say nothing (or, at least, not so much) about interactive computation, and new, more general models were required, such as the persistent turing machine (PTM) [16]. After Milner first emphasized the role of interaction in computational systems [31], Wegner made interaction emerge as a first-class issue, which is at the core of both computer research and technology.

The above parallel between the history of ideas in physics and computer science might then be argued (and maybe with some reasons) to be more speculative than scientifically well-founded. However, it seems to indicate that the understanding of complex systems cannot come from the mere study of the nature and inner dynamics of the basic system constituents, but requires instead that the nontrivial patterns of their mutual interaction be devised out and suitably modelled.

3 Interaction and Environment

3.1 Interactors in Evolutionary Biology

Evolutionary biology is a particularly interesting field for us here, given the fact that it deals with the long-term behaviour of complex living systems.

Evolutionary biology aims at understanding and explaining the way in which first-class components of biological systems (such as cells, organisms, species) change over time—where the notion of time spans from the small scale of individual living organisms up to the geological scale. After nearly one century and a half, one of the reference works in the field is still the monumental *Origin of Species* by Charles Darwin [8], a milestone of human knowledge indeed. According to the basic Darwinian theory, the process of natural selection is grounded on three basic facts (overproduction of offspring, variation, and heritability) plus one core mechanism, that is, differential reproductive success within evolving local environments. Besides the obvious general relevance of such a matter, what is really of interest here is the subject of the intense and passionate discussion that has kept going on during the last decades among evolutionary biologists. The matter of discussion, labelled as the *replicator approach vs. interactor approach* issue, focused on how "differential selection" actually occurs, and what is the unit of (differential) selection.

In general, a replicator can be described as an "entity that passes on its structure directly in replication", and an interactor as an "entity that directly interacts as a cohesive whole with its environment in such a way that replication is differential" [25, page 318]. The so-called "replicator approach" sees all evolution as proceeding through genes as units of reproduction, with the interacting entities (the organisms) merely built up as a result. Along this line, the founders of modern gene selectionism, such as Dawkins [9] and Williams [53], advocated the prominence of replicators in the selection process: the real unit of selection is represented by the genes, struggling for their eternal life, indefinitely reproducing themselves through higher-level organisms working as mere passive recipients, vehicles for gene existence. By contrast, the "interactor approach" obviously acknowledges the role of replication in selection (already assumed by Darwin long before the gene replication mechanism was known), but advocates the prominence of interactors as units of reproduction. Along this line, selection is obviously defined in terms of *both* notions (replicator *and* interactor) as the result of the differential proliferation/extinction of interactors in terms of the differential perpetuation of replicators.

However, according to Stephen Gould, causality in selection resides in interaction with the environment, and not in replication [17, page 615].[3] In particular, the key point in Gould's theory is that genes (the replicators) do not interact *directly* with the environment—so, they are not exposed directly to change. Rather, genes indirectly operate via the organisms (the interactors) that live, behave, interact and die—and typically reproduce, thus perpetuating replicators as a secondary effect. In doing so, interactors build up the process of differential selection that determines the evolution of biological systems over time: interaction with the environment can then be viewed as the main force that drives biological evolution.

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[3] See also [17, page 623]: "units of selection must, above all, be interactors".

3.2 The Role of the Environment in Computational Systems

At a first glance, what happened in the evolutionary biology field resembles some of the research developments that occurred in computational sciences in the last decades, and in particular in the MAS field. At the very beginning (after Darwin, but before Mendel's gene theory was commonly understood and accepted) the very notion of replicator was an empty box: heritability of features was accepted, but no scientific explanation of how this could happen was available. As a result, when the gene replication mechanism was finally understood and modelled, and used as a basis for the whole Darwinian theory, excitement put all the emphasis upon such a mechanism—so, for instance, explaining everything in terms of genes and their duplication was quite natural. Only subsequently, after Hull and Gould, organisms—rather than genes—were finally recognized as the units of selection, and interaction with the environment was understood as a primal issue in natural selection.

More or less in the same way, the power of the notion of agency made research on MASs focus for a long time on the individual agent issues—and in particular on principles of the agent inner architecture and functioning. Even the revolutionary work of Brooks on robotic agents [5], with its notion of *situated intelligence* pointing out the inextricable relation between intelligent behaviour and the environment, was not immediately appreciated. Only in the last few years, interaction with the environment has finally been recognized as an essential issue for understanding agent and MAS evolution over time. It is not by chance that only in 2004 was the first workshop on "Environments for MultiAgent Systems" held, at the 3rd world-wide MAS conference [52]. The recognition of the role of the environment in the MAS field recently came from subfields such as agent-oriented software engineering (AOSE) [3]. There, AOSE methodologies promoted the environment as a first-class entity in the engineering of situated computational systems, putting the interaction of agents with their environment at the core of the engineering process [34]. Under this perspective, agents are the interactors of MASs, and it is their observable behaviour while interacting with the environment—their *situated interaction*, along Brooks' line—rather than their inner structure, that determines the evolution of the system as a whole.

3.3 Interaction through the Environment

When trying to understand how interaction with the environment affects the properties and behaviour of complex systems, social biological systems can be used as a powerful source of inspiration. In the context of animal societies, like ant or termite colonies, *stigmergy* is a well-known form of indirect interaction occurring through the environment—and exploiting the physical properties of the environment. There, individuals (such as ants or termites) interact by exploiting shared environmental structures and mechanisms to store and sense some sorts of signs (such as pheromones in the case of ant-based systems), as well as processes transforming them (such as evaporation/aggregation of pheromones) which also depend on the nature of the environment [18].

Complex social systems of this kind, in short, exhibit independent and autonomous individual components, which interact with each other in several nontrivial ways, but mainly by locally modifying the surrounding environment. The modification is through *mediators* (e.g., the pheromones) that physically embody an information content, and whose characteristics (e.g., the rate of decay) affect the nature of interaction among components, and, in the end, the global behaviour of the system and its evolution over time. The many desirable features of such systems—like emergent behaviours, some forms of global intelligence, and system self-adaptation to changing environment conditions—that can stem from stigmergic coordination, has inspired a number of stigmergy-based approaches to the coordination of computational systems [21, 24]. Other models, like the ones based on computational fields [30], or generalizing stigmergy [41], add some more to the notion of situated interaction, which is going to be clearly developed in the next section through the specific notion of mediated interaction.

4 Mediated Interaction

4.1 Mediated Interaction in Human Organizations

Activity theory [29, 49, 13] and distributed cognition [27] are two approaches to the study of human social activities that have deeply focused on the role of interaction within complex human organizations. The first result clearly emerging from these social/psychological theories is that *every individual as well as social activity in complex societies is mediated* [46, 2].

This is particularly clear in the context of activity theory (AT), where *mediation* is among the basic principles that constitute the core of the AT framework: human activity is always mediated by a number of tools or *artifacts*, both external and internal. The mechanism underlying artifact mediation is the formation of *functional organs*, i.e., the combination of natural human abilities with the capacities of external components—artifacts—to perform a new function of to perform an existing one more efficiently.

Then, any activity can be characterized by a *subject*, an *object* and by one or more *mediating artifacts*: (i) a subject is an agent or group engaged in an activity; (ii) an object is held by the subject and motivates the activity, giving it a specific direction (the objective of the activity); (iii) the mediation artifacts are the tools that enable and mediate subject actions toward the object of the activity. The mediating artifacts can be either physical or abstract/cognitive; from cognitive examples such as symbols, rules, operating procedures, heuristics, individual/collective experiences, languages, to physical entities, such as maps, blackboards, synchronizers, semaphores, and so on. The definition is clearly oriented to bring to the foreground not only individuals (subjects) and their cognitive aspects, but also the context where they play, and the continuous dynamic processes that link subjects and the context.

According to AT, mediating tools have both an *enabling* and a *constraining* function. On the one hand, they expand the possibilities of individuals to manipulate and transform different objects. On the other hand, the object is perceived and manipulated not "as such" but within the limitations set by the tool. Mediating artifacts shape the way human beings interact with reality. According to the principle of internalisation/externalisation, shaping external activities ultimately results in shaping internal ones. Artifacts embody a set of social practices, and their design reflects a history of particular use: they usually reflect the experiences of other people who have tried to solve similar problems at an earlier time and invented/modified the tool to make it more efficient.

Mediating artifacts are created and transformed during the development of the activity itself and then they carry with them a particular culture, the historical remnants of that development. So, the use of tools is a means for the *accumulation* and *transmission* of *social knowledge*. They influence not only the external behaviour, but also the mental functioning of individuals using them.

Latest research in AT—applied in particular in the context of CSCW (Computer Supported Cooperative Work)—focuses on the characterization of activities and artifacts in the context of collective human work [2]. AT describes cooperation as a collaborative activity with one objective but distributed between several actors, each performing one or more actions according to the shared goal of the work. The relationships between the individual work activities and the work activities of his/her fellow workers is subject to a division of work, and is regulated by different rules and norms, more or less explicit. According to this research, a collaborative activity can be structured in three *hierarchical levels*: *co-ordinated*, *co-operative*, and *co-constructive* [2, 12]. Mediating artifacts are *used* to encapsulate and automatise the routine flow of interaction between the participants to the collaborative activities at the co-ordination level. By contrast, they are *designed* and *forged* at the co-operation level, where participants focus on a common objective of the activity, and then on the means (the artifacts) for realizing it.

The notion of *dynamic transformation* between the three hierarchical levels of collaborative activities is also central to AT [2]. Transformations are strictly related to the stability of the means of work and of the object of work. Upward transformations correspond to the activity of evaluating and re-thinking either the means of work, or the object of the work itself. Instead, downward transformations correspond to the resolution of conflicts and problems, which is reified in the lower levels, possibly embodied in a newly-forged mediating artifact. Correspondingly, *reflection* on the means of work—going from co-ordination to co-operation—and *routinization*—going from co-operation to co-ordination—are the most important transformations. The former happens when the coordinated flow of work, relying on stable means of work such as scripts, rules, mediating artifacts in general, needs to be co-operatively re-established according to the object of work; the reasons can be either co-ordination breakdown, or a deliberate re-conceptualization of the way the work is currently achieved. The latter works in the opposite directions, by re-establishing co-ordinated work where the means of collaboration are stabilized, and new/adapted mediating artifacts are provided to be exploited by participants in the co-ordination stage.

4.2 Mediated Interaction in Computational Systems

Activity theory has recently found its applications within computational sciences, in particular in CSCW [32] and agent-oriented software engineering [40]. More generally, the conceptual framework of AT can find its use beyond the scope of human collaborative activities, wherever systems can be conceived as made of independent entities, which autonomously act within a structured context to achieve their own goals as well as collective objectives. This is for instance the sort of context that is typical of distributed and concurrent systems, in particular those modelled or built according to the agent paradigm.

AT is a source of a number of interesting ideas for computational systems. As far as interaction is concerned, we can synthesize at least three major points:

Beyond direct interaction — First of all, interaction is always mediated. Direct interaction is only an interpretation, which only works when the medium of the interaction can be abstracted away without any loss in the understanding of the state and dynamics of the interaction. *Environment* plays a key role here, since it generally works as the natural *locus* of the mediation: the central issue becomes how to control and instrument the environment where computational systems live and work, in order to enable and coordinate the interaction among the computational entities that are there immersed.

Mediating artifacts — Mediated interaction is encapsulated within first-class entities, the mediating artifacts. Mediating artifacts play a twofold role: constructive/enabling, and constraining/governing. On the one hand, they are the means that enable interaction, and allow software engineers to define and shape the space of component interaction. On the other hand, by determining admissible interactions, they constrain the components' observable behaviour, and make it possible to govern the space of interaction.

- Mediating artifacts are then essential tools in the modelling and engineering of complex computational systems, and are subject of theories and practices that are typically different from the ones adopted for interacting components. The central role of abstractions working as mediating artifacts is already evident in several approaches coming from computer science, software engineering and artificial intelligence. The notion of coordination medium within the area of coordination models and languages [6, 15]—like Linda tuple spaces [14] or TuCSoN tuple centres [38]—blackboards in distributed artificial intelligence [7], channels in the core calculi for interaction [31] or component composition [1], connectors in software architectures [43].

Analysis and synthesis of the interaction space — The notions of mediated interaction and mediated artifact deeply impact on methodologies for the construction of computational systems, at every stage of the engineering process. The three levels for collaborative activities in AT—co-construction, co-operation, co-ordination—can be seen as representing distinct stages of an interaction-oriented engineering process, covering the specification, design, validation, run-time verification and modification of mediating artifacts.

- Dynamic transformation between the three levels is the crucial point for both the analysis and the synthesis in the interaction-oriented engineering process: on the one hand, mediating artifacts are the subject of dynamic observation—observing their state and history makes it possible to analyse and understand the dynamic behaviour of complex systems; on the other hand, mediating artifacts are the basic bricks for computational systems—they are designed and forged to shape and govern the space of component interaction.
- Dynamics also means that systems can be changed at run-time, by suitably observing, understanding and modifying mediating artifacts, so as to intervene on the dynamics of system interaction. By featuring properties such as predictability, inspectability, controllability, malleability and linkability [40], mediating artifacts promote engineering practices aimed at promoting social intelligence, system adaptation and self-organization of computational systems [37].

5 Institutions and Infrastructures

5.1 Institutions and Infrastructures in Human Societies

The most recent accounts of the research by cultural anthropologists tend to recognize some repeated patterns in the formation and evolution of human societies in the last ten thousands years—not only in the European and North-American history, but around the globe. In particular, the many different forms taken by human societies are often divided in half a dozen of categories, that differs under many aspects: number of members, settlement pattern, basis of relationships between members, and (in general) form of government [11].

However, it can be easily seen that most of the above issues are so to say "dependent" variables, where the main "independent variable" is the number of people constituting a society. How people are settled, how they relate each other, how they resolve conflicts, etc., are mostly dependent on the number of members of the society.

Under certain favourable conditions (such as the abundance of food), successful societies (that is, those forms of human organization that guarantee more chances of survival to its members, and thus, to themselves) tend to grow in size. When they grow over certain limits, the institutions that govern them are forced to change—and societies change with them. For instance, in a band (the tiniest form of society, with dozens of members at most) or a tribe (hundreds of members), power is shared among peers, and conflict resolutions between members is handled informally on a case by case basis: no formal rules nor recognized institutions (apart from shared habit and oral tradition) help in composing conflicts. By contrast, larger societal forms like chiefdoms (with thousands of members) typically evolve by requiring some forms of central government (with chiefs exerting their powers over other members) and institutions (with bureaucrats ruling some aspects of social life, like exacting tributes, or resolving conflicts between members). The largest known forms of human organizations (states) typically develop military forces, police, written rules (laws), and all the well-known (to us) social institutions that shape and govern modern forms of human societies.

In the end, this is clearly a problem of *scale*: direct interaction and sharing of power among (human) peers does not work at the large scale. By freely reinterpreting the results from [11], this is due to several reasons:

Mutual recognition — Any form of cooperation (or even conflict avoidance) between members of a society depends on their capability to recognize each other as members of the *same* society, even if they do not know each other directly. When mutual recognition can no longer be based on direct knowledge, as in the case of large number of members, only formally defined social institutions (common, county, nation, state, . . .) can ensure mutual recognition by providing a social, shared notion of identity, not based on kinship or friendship of any kind.

Monopoly of force — When the number of the society members is too high, the number of possible conflicts grows so much that the use of force by conflicting members to resolve conflicts becomes potentially disruptive for the society as a whole. The development of centralised institutions monopolising force and preventing/solving potentially violent disputes through both administrative and military infrastructures (judiciary, prisons, police, army) become inescapable when a society grows in size.

Delegation of Power — In small societies, decision making can be a globally shared process where everybody is involved in the discussion and in the final deliberation. In the case of large societies, this may obviously lead to an unbearably inefficient process, and has typically produced many forms of delegation of power to a small number of selected members (leaders, majors, kings, presidents) or institutions (oligarchs, senates, parliaments), that can ensure timely convergence of the decision process.

Redistribution of goods — While trading in small societies can be handled on a peer-to-peer basis, the exchange of goods needs a more complex organization in larger societies. Political and economical conventions, regulations, norms and laws are required, and call for suitable institutions to enact them, and rule economic interaction among a vast number of society members.

Distribution of space and resources — Resources available to a small society, like living space, can be distributed on an ad hoc basis, and accessed almost freely. When population increases, and its density grows, distribution of space (and access to shared resources like water and food) requires a more structured societal organization, and the introduction of new notions like private property, right to access, right to use and so on.

5.2 Institutions and Infrastructures in Computational Systems

So, what are we going to learn for software systems, from the long history of successful complex systems like human societies? A number of interesting results have the potential to be applied to computational systems in general. For the sake of simplicity, however, in the following we will refer in particular to MASs, as they present the deepest similarities with human societies among the many classes of computational systems known today.

First of all, we recognize that large systems composed of many individual members cannot be based on peer-to-peer relations: interactions between members have to be governed and ruled by suitable *institutions*. How much is "large" for a software system we cannot derive from here: a human in a human society is not the same as an agent in a MAS. What is not likely to change, however, is that *at some scale*—whichever it is, thousands, millions or billions of agents—the same sorts of problems are likely to arise in increasingly complex MASs that already rose in human society growing in size over time, and eventually make the development of social institutions almost mandatory.[4] On the other hand, this also corresponds in MAS research to the recent trend toward institutions meant to govern the complexity of software systems by harnessing interaction among components—as illustrated by the nowadays emerging notions of *e-institution* [33], and *logic-based electronic institution* [47] among the many others.

Institutions for large agent societies have to provide solutions to problems such as the ones for large human societies pointed out above: mutual

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[4] The argument that agents have not the same limitations as humans is exact but, at the same time, misleading: limitations (for instance, in memory) might be different (for instance, in size), but they exist indeed. So, there will always exist an appropriate scale of complexity where agents (and agent societies) encouter the same sort of problems as humans (and human societies).

recognition between members of a MAS, support for specialized agent roles, resolution of conflicts between agents, concerning for instance access to shared resources, enaction of global laws governing the behaviour of agents and promoting cooperative attitude—or at least, efficient decision making in large MASs.

As an aside it has also to be noted that institutions in human societies (the army, the police, the parliament, the judiciary) are not individual human beings—as obvious as it may seem. Institutions are made of humans, but none of them is an individual human. Even more, this simple consideration is not limited to collective institutions: even kingship, for instance, is an institution that cannot be identified or confused with the individual, temporary king. Correspondingly, institutions in MASs are (in principle) not agents: agents may participate in them and make them work, but no agent is an institution.[5] Instead, agent institutions are naturally embodied in agent infrastructures, governing agent interactions within a MAS—as pointed out by the notion of *governing infrastructure* in [35].[6]

In the same way as infrastructures in human societies provide services to individuals and organizations (the communication, the health care, the security, the physical mobility infrastructures, among the many others), agent infrastructures are meant to provide services to agents and agent societies. Correspondingly, in the same way as traffic lights or street signs govern car traffic (allowing the more or less peaceful coexistence of car drivers), runtime abstractions provided by an agent infrastructure can be used by MASs to rule agent access to shared resources, and to allow several potentially conflicting agents to achieve their respective, unrelated goals in a coordinated way.[7] By further developing the conclusions of previous section, this is most properly achieved through the use of mediating artifacts, provided by agent infrastructures as runtime abstractions, as in the case of workflow engines for MASs [39], or of the general notion of *coordination services* [48].

The final point here is then clear: institutions, and the infrastructures that enforce them, are required to rule and govern the interactions among members of large, complex societies—without them, these societies are doomed to instability, chaos and final failure. Accordingly, the modelling and engineer-

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[5] The fact that institutions can be interpreted (as in [4]) or even implemented (as in [45]) as agents can be of some use, sometimes, but does not affect the general principle that institutions are not agents.

[6] In the same way as they are not agents, institutions are not even infrastructures: rather, agent institutions are naturally *implemented upon* agent infrastructures.

[7] While *agentification* of resources—that is, the view of resources as agents—is usable and useful in particular cases, it is not the most suitable and effective approach in general. In fact, as argued for instance in [42], agents *use* resources (through virtual physical actions), while they *speak* to other agents (through communicative actions): resources have interfaces, agents have not. In the end, agentification is nothing but the obvious result of the bias toward communication (against physical action) of current agent research.

ing of complex computational systems like MASs require the definition and enaction of *computational institutions*, embodied in hardware/software infrastructures which provide suitable runtime abstractions to mediate and govern the interaction between the individual components of a system.

6 Final Remarks and Conclusions

Many other possible sources of inspiration are not accounted for by this chapter: the implications of the Heisenberg *uncertainty principle* [22], basically stating that the interaction involved in the observation of phenomena intrinsically affects their behaviour; the part of modern biology concerning modelling and simulation of biological processes, and known as systems biology, which aims at system-level understanding of biological systems [28]; the notion of emergence [23], some theories of economics, and surely many others, even from the computer science field. But the goal here is not to be exhaustive.

Instead, our aim in this chapter is first of all to point out how the study of interaction as a first class subject of research is at the core of a number of diverse scientific areas dealing with complex systems; then, to show that the patterns emerging from such a heterogeneous range of scientific disciplines can be exploited as transdisciplinary bridges fruitfully connecting different areas, and bring their results to computer science.

Along this line, we try to devise an as-simple-as-possible conceptual path:

1. Interaction as a first-class subject of study — Complex systems cannot be described, understood or built by merely dealing with the nature and behaviour of their individual components—in the same way as fundamental physics cannot be understood by merely focusing upon the nature of individual particles. Instead, the study of interaction *per se* is a central issue, which calls for special, interaction-oriented paradigms, models, technologies and methodologies aimed at modelling and engineering complex systems.
2. Environment, or the situatedness of interaction — The individual components of a system cannot be studied or understood separately from the environment where they live and interact—in the same way as evolution of human societies cannot be understood separately from the environment where they live. Studying the environment of a system, its nature and dynamics, and its interaction with the system components, is a fundamental precondition to the understanding of the essence and evolution over time of complex systems of any sort.
3. Mediated interaction, and the artifacts — Interaction is always mediated, and the nature of mediators affects interaction—in the same way as the nature of pheromones determines the behaviour of ants and ant colonies. The notions of mediator and mediating artifact are essential tools in the analysis and synthesis of the space of interaction within complex systems.

4. Institutions and infrastructures — Institutions are required to rule and govern the interactions among participants of large, complex systems—in the same way as they are required by contemporary human societies. In order to enact institutions, infrastructures are needed which mediate and govern the interaction between the individual participants of a complex system, by encoding and enforcing institutional rules, norms and laws.

As the reader may easily note, the above interaction-related patterns do not require for their general description any reference to the nature of the complex system involved: be it either a physical, a biological, a social, or a computational system, all the above considerations straightforwardly apply. Drawing from the wide range of disciplines dealing with the study of complex systems, computational sciences can finally find new paths for overcoming complexity, and possibly constructing the artificial systems of tomorrow.

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