Complexity & Interaction: Blurring Borders between Physical, Computational, and Social Systems
Preliminary Notes

Andrea Omicini and Pierluigi Contucci

Alma Mater Studiorum – Università di Bologna
{andrea.omicini,pierluigi.contucci}@unibo.it

Abstract. Complex systems of any type are characterised by autonomous components interacting with each other in a non-trivial way. In this paper we discuss how the views on complexity are evolving in fields like physics, social sciences, and computer science, and – most significantly – how they are converging.
In particular, we focus on the role of *interaction* as the foremost dimension for modelling complexity, and discuss first how *coordination* via mediated interaction could determine the general dynamics of complex software system, then how this applies to *complex socio-technical systems* like social networks.

Keywords: Complex systems, interaction, interacting systems, statistical mechanics, coordination models, socio-technical systems

1 Complexity & Interaction: An Introduction

The notion of complexity is definitely a multi-disciplinary one, ranging from physics to biology, from economics to sociology and organisation sciences. Most interestingly, systems that are said "complex" are both natural and artificial ones: so, for instance, we observe and model complex physical systems, and at the same time we design and build complex computational systems.

Along this line, moving from the pioneering work of Simon [?] on complex artificial systems – whose acceptation of complexity and complex system is the one implicitly adopted here –, it is nowadays widely recognised that there exist some "laws of complexity" that characterise any complex system, independently of its specific nature [?]. No matter whether we are modelling the behaviour of a human organisation, the life of an intricate ecosystem, or the dynamics of a huge market-place, we can anyway expect to find some repeated patterns, some shared schema, some common laws that make all such systems look similar—of course, when they are observed at the right level of abstraction. However, the exact source of what all complex systems share, the precise nature of such common factors to which all complex systems might be reducible, is still unknown in essence.

In this paper we argue that *interaction* – its nature, structure, dynamics – is the key to understand some fundamental properties of complex systems of any type. Accordingly, in this preliminary notes we first elaborate on the role of interaction in complex systems, then we provide some perspectives on how the evolving views on complexity coming from physics and computer science could be seen as converging, by adopting complex socio-technical systems such as social networks as a key case study.

2 Complexity & Interaction in Computational Systems

> ... by a complex system I mean one made up of a large number of parts that interact in a non simple way [**?**]

Complexity is nowadays one of the most relevant traits of the systems of interest in many scientific fields. In particular, interaction is recognised as a fundamental dimension for modelling and engineering complex computational systems [**?**]: in a world where software systems are made of an always-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.

In [**?**] the study of interaction as a first-class subject of research is shown to be at the core of a number of diverse scientific areas dealing with complex systems, whose results are "bridged" towards computer science, devising out a linear conceptual path:

Interaction — Complex systems cannot be described, understood, or built by merely dealing with the nature and behaviour of their individual components. Instead, dealing with *interaction* as first-class subject of study is a key issue: this calls for special, interaction-oriented paradigms, models, technologies, and methodologies aimed at modelling and engineering complex systems.

Environment — Individual components of a system cannot be understood separately from the *environment* where they live and interact. Studying the environment where a system is situated, its nature and dynamics, as well as its interaction with the system components, is a fundamental pre-condition for understanding the essence and evolution over time of complex systems of any sort.

Mediated interaction — Interaction is always *mediated*, and the nature of mediators affects interaction. The notion of *mediator*, along with its structure and behaviour, is essential for modelling and engineering the space of interaction within complex systems.

Infrastructure — In order to govern the interactions among participants of large, complex systems, a suitable *infrastructure* is required, which could enforce collective laws and norms to rule the interaction among individual components, as well as the system and its environment—essentially, by enacting laws through a coherent apparatus of mediators.

It is quite easy to see that the above interaction-related notions – along with the conceptual path they implicitly sketch – do not pertain to complex computational systems only: instead, as discussed in [?], they apply – in diverse ways – to either physical, biological, social, or computational systems.

When applied to computational systems, the same notions basically draw the foremost lines of evolution of contemporary computational systems: *(i) interaction* has become an essential and independent dimension of computational systems, orthogonal to mere computation [?,?]; *(ii) environment* is nowadays conceived as a first-class abstraction in the modelling and engineering of complex computational systems, such as pervasive, adaptive, and multi-agent systems [?]; *(iii)* environment-based *mediation* [?] is the key to designing and shaping the interaction space within complex software systems, in particular socio-technical ones [?]; finally, *(iv)* middleware and software infrastructure provide complex socio-technical systems with the mediating abstractions required to rule and govern social and environment interaction [?].

The nature, structure, and behaviour of such mediators are better discussed in Subsection 4.1, where the notion of *coordination medium* is introduced and reviewed.

3 Complexity & Interaction in Statistical Mechanics

Whereas the concepts illustrated in the previous section generally apply to many sorts of systems, quite a different view over complexity comes from physics, and in particular from *statistical mechanics*. Statistical mechanics is the branch of theoretical physics born after a set of ideas and methods, originally introduced by Boltzmann [?], used to de-axiomatise thermodynamics—i.e., to derive its laws from those of mechanics by means of probability methods. There, the key point is to relate the *macroscopic* observables quantities – like pressure, temperature, etc. – to suitable *averages* of *microscopic* observables—like particle speed, kinetic energy, etc. Since the method works based on the laws of large numbers, it turns out to be effective for those systems made of a large number of particles / basic components.

In a similar way as computer science, statistical mechanics has expanded beyond its origins: first, into many directions within physics; then, in the last decades, towards fields as diverse as biology [?], economics [?,?], and computer science itself [?,?], while its relevance in social sciences is growing fast as well. Cross-fertilisation with all those assorted fields concerns many different aspects, but focuses in particular on the notion of *complexity* as it emerges from statistical mechanics. In order to introduce its main features, it is useful first of all to review the basic properties of statistical mechanics systems, starting from the elementary classical cases up to the more recent and refined ones.

3.1 Interaction in Statistical Mechanics

Historically, the ideal gas behaviour is probably the first example of a thermodynamic system successfully understood by adopting statistical mechanics method.

The laws governing its behaviour may indeed be deduced, with elementary methods of probability, from physical laws like conservation of energy and momentum for the particles the gas is composed of, with the crucial identification of the mean kinetic energy with the temperature of the system.

The key point here is that the mathematical model of the ideal gas contains the assumption of *mutual independence* among particles, that is, the behaviour of the particles, as well as the resulting overall behaviour of the system, is not affected by their mutual *interaction*: the factorisation law that mathematically encodes the property of independence is related to the microscopic fact that the ideal gas particles do not interact with each other. Under this assumption, the probability distribution of the whole system is the product of those of each particle that composes it—in computer science terms, the properties of the system can be *compositionally* derived by the properties of the single components [**?**]. The foremost consequence of the above assumption is that the system as a whole does not display any type of macroscopic sudden shift, or abrupt change: in physics, such a sort of system is technically said to have no *phase transitions*.

The introduction of an interaction among particles changes structurally the macroscopic properties and, correspondingly, the mathematical ones. The probability distribution of the system does not factorise anymore – in computer science terms, the system is no longer compositional [**?**] –, and the study of its properties becomes much more challenging. *Interacting systems* – that is, systems where particles do not behave independently of each other – are the only suitable candidates to describe real cases beyond the idealised ones. The versatility of interacting systems in the modelling of physical systems is especially proven by the fact that they are the only ones capable to explain phase transitions – like liquid-gas transition – and much more, such as collective emerging effects. While a system made of independent parts can be represented by isolated single nodes, an interacting system is better described by nodes connected by lines or higher-dimensional objects. From the point of view of information and communication theories, an ideal non-interacting gas is a system of non-communicating nodes, whereas an interacting system is made of nodes connected by channels.

3.2 Complexity in Statistical Mechanics

Interaction is a necessary ingredient for complexity in statistical mechanics but definitely not a sufficient one. The simplest standard prototype of an interacting system is the one made of magnetic particles. There, individual particles can behave according to a magnetic field which leaves their probabilistic independence undisturbed. At the same time, two magnetic particles interact with each other, and the strength of their interaction is a crucial tuning parameter to observe a phase transition. If the interaction is weak, the effect of a magnetic field is smooth on the system; instead, if the interaction is strong – in particular, higher than a threshold – even a negligible magnetic field can cause a powerful cooperative effect on the system. The system can be in one of two equilibrium states: the up and the down phase.

Complexity arises when the possible equilibrium states of a system grow very quickly with the number of particles, regardless of the simplicity of the laws governing each particle and their mutual interaction—in other terms, roughly speaking, complexity is much more related to size in number, rather than to complexity of the laws ruling interaction. Such view of complexity in statistical mechanics emerged in a fundamental achievement of theoretical physics, that is, the solution to the so-called mean field *theory of spin glasses* [**?**]. Beside the physical origins of that theory, the mathematical model describing those systems – see [**?**] for a rigorous account – accounts not just merely for interaction between particles: instead, it also features the property of being alternatively either *imitative* or *anti-imitative* with the same probability. There, prototypical cooperation and competition effects are both present, and the resulting emerging collective effect is totally new. The equilibrium state space that was identified is endowed with a hierarchical structure: configurations are organised in families, families in superfamilies, and so on. From the geometrical point of view, those spaces are sometimes called *ultrametric*, or tree-like.

3.3 From Statistical Mechanics to Social Systems

In order to illustrate the growing levels of complexity, along with the increasing relevance of interaction, a parallel with social systems is surely of some use here. A group of isolated individuals neither knowing nor communicating with each other is the typical example of a *compositional* social system—that is, a system whose global behaviour results from the independent "sum" of the behaviour of its single components. No sudden shifts are expected in this case at the collective level, unless it is caused by strong external exogenous causes.

In order to obtain a collective behaviour displaying genuinely endogenous phenomena, the individual *agents* should be in a state of exchange of information—i.e., they have to meaningfully interact with each other. The foremost issue here is that *the nature of the interaction determines the nature of the collective behaviour* at the aggregate level. For instance, a simple imitative interaction is capable to cause strong polarisation effects even in presence of extremely small external inputs. Nevertheless, in order to obtain the real complexity of a social system, with clusters iteratively organised in sub-clusters, the interaction ought to be not only *imitative* (cooperative) but also *counter-imitative* (competitive), randomly extracted with equal probability.

There are clear indications that the complex behaviour of many observed socio-economic systems – and in particular the crisis events [**?**] –, can be approached with the quantitative tools developed within those statistical mechanics ideas. Among the issues for future investigations, *structural stability* of modern society is likely to be key. In such a context, research has to face the challenge of devising out the opportunities to take and the dangers to avoid in relation to the fast changes underwent by social connectivity [**?**,**?**] that, in the last decades, has witnessed an enormous increase.

4 Perspectives: Coordination & Socio-Technical Systems

In order to draw some consequences from the above notes about complexity and interaction in computational, physical, and social systems as well, two are the possible starting points.

First of all, while physical systems are to be observed, understood, and possibly modelled, computational systems are to be designed and built. In particular, whereas for physical systems the laws of interaction, and their role for complexity, are to be taken as given, to be possibly formalised mathematically by physicists, in the case of software systems the laws of interaction have first to be defined through amenable abstractions and computational models by computer scientists, then exploited by computer engineers in order to engineer computational systems.

Secondly, a particularly relevant class of social systems, nowadays, is represented by socio-technical systems – such as social platforms like FaceBook [?] and LiquidFeedback [?], for instance –, where active components are mostly represented by humans, whereas interaction is almost totally regulated by the software infrastructure.

Accordingly, in the remainder of this section we first suggest how coordination models and languages can be used to define the laws of interaction in complex computational systems. Then, we derive a novel perspective over socio-technical systems, where scientific and technical tools from both computer science and physics can be exploited to assess new macroscopic properties of complex systems.

4.1 Coordination Media for Ruling Interaction

Defining the abstractions and the computational model for ruling the interaction space in computational systems basically means to define their *coordination model* [?,?,?]. Coordination models are typically enforced via suitable *coordination middleware*, providing *coordination media* – like LINDA tuple spaces [?], or Reo channels [?] – as the mediators for the interaction among *coordinables* – that is, the components of the system representing the coordinated entities –, which enforce the *coordination laws* that rule interaction among coordinables [?]. According to [?], coordination laws shape the interaction space by *constraining* the admissible interactions among components, and between components and the environment—that is, by defining the acceptable perceptions and actions by coordinables, as well as their mutual coordination, independently by their inner structure and behaviour.

Roughly speaking, this means that the global properties of complex coordinated systems that depend on interaction can be enforced through an appropriate choice of the coordination model, essentially based on its expressiveness—that is, the ability to capture and inject suitably-expressive laws of coordination governing system interaction [?,?]. For instance, tuple-based coordination models have been shown to be expressive enough to support self-organising coordination patterns for nature-inspired distributed systems [?].

Along this line, it is quite natural to draw a parallel with physical systems, where the nature of interaction among components (particles) changes structurally the macroscopic properties of systems. In particular, as discussed in Section 3, interacting systems are the only ones capable to model phase transitions, and, more generally, collective emerging effects.

So, in the same way as the study of stigmergy coordination in social insect colonies [**?**] has proven how coordination models can be used to support stigmergy in computational systems, and also to develop new coordination patterns such as *cognitive stigmergy* [**?**,**?**], the study of physical systems could possibly lead to the definition of new sorts of global, macroscopic properties for computational systems inspired by physical ones. For instance, an interesting line of research could involve trying to understand *(i)* whether notions such as *phase*, *phase transition*, or any other macroscopic system property, could be transferred from statistical mechanics to computer science; *(ii)* what such notions would imply for computational systems; and *(iii)* which sort of coordination model could, if any, support such notions.

4.2 A Twofold View of Socio-Technical Systems

A particularly-interesting sort of complex system nowadays are the so-called socio-technical systems—that is, artificial systems in which human interaction plays a central role. The so-called Web 2.0 [**?**] and social platforms like FaceBook or LiquidFeedback are outstanding examples of such as sort of systems, whose interest here comes from their twofold nature of both social systems and computational systems [**?**,**?**]

As complex social systems, their complex behaviour is in principle amenable of mathematical modelling and prediction through notions and tools from statistical mechanics, as discussed in Subsection 3.3. As complex computational systems, they are designed and built around some (either implicit or explicit) notion of coordination, ruling the interaction within components of any sort—be them either software or human ones.

Altogether, socio-technical systems are sorts of social systems whose macroscopic properties can be described by exploiting the conceptual tools from physics, and at the same time be enforced by the computational abstractions made available by coordination models. In other terms, social platforms – and complex socio-technical systems in general – are precisely those sorts of systems where the acceptation of complexity as developed by statistical mechanics (and subsequently expanded to physics and social systems), along with the corresponding mathematical tools for behaviour modelling and prediction, can finally meet the abstractions and tools from computer science (in particular, coordination models and languages) that make it possible to suitably shape the interaction space within complex computational systems. As a result, we envision complex socio-technical systems whose implementation is based on suitable coordination middleware, and whose macroscopic properties can be modelled and predicted by means of mathematical tools from statistical physics.

5 Conclusion

In this paper we elaborate on the notion of complexity as it emerges from fields like physics and computer science, and foresee some possible lines of convergence. In particular, we focus on interaction as the key issue for complex systems, discuss its role in physics and computer science, with a perspective on social systems. Then, we elaborate on coordination models and middleware as the possible sources of abstractions and technology for enforcing global properties in complex computational systems, which could then be modelled as physical systems, and engineered as computational ones.

In particular, we suggest that socio-tecnical systems such as large social networks could represent an ideal case study for the convergence of the ideas and tools from statistical mechanics and computer science, being both social and computational systems at the same time. To this end, in the near future we plan to experiment with social platforms like FaceBook and LiquidFeedback, by exploiting coordination technologies for setting macroscopic system properties, and statistical mechanics tools for predicting global system behaviour.

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