Complexity in Computational Systems: The Coordination Perspective

Andrea Omicini
andrea.omicini@unibo.it

Dipartimento di Informatica – Scienza e Ingegneria (DISI)
Alma Mater Studiorum – Università di Bologna a Cesena

Complex Systems Physics / IMT-UniBo
Bologna, Italy, 15 February 2018

Next in Line. . .

Modelling vs. Building Complex Systems

Everybody knows that...

- the notion of *complexity* is definitely a *multi-disciplinary* one, ranging from physics to biology, from economics to sociology and organisation sciences
- systems that are said *complex* are both natural and artificial ones

Physical vs. computational complex systems

- as they are *natural systems*, we *observe* and *model* complex physical systems
- as they are *artificial systems*, we *design* and *build* complex computational systems

Complexity in Computational Systems I

A "simple" notion of complexity to start with

. . . by a complex system I mean one made up of a large number of parts that interact in a non simple way [Simon, 1962]

. . . towards interaction

- if some "laws of complexity" exists that characterise any complex system, *independently* of its specific nature [Kauffman, 2003]
- we focus on interaction – its *nature*, *structure*, *dynamics* – as the key to understand some fundamental properties of complex systems
  - in particular *complex computational systems*

Complexity in Computational Systems II

An essential source of complexity for computational systems is

interaction

[Goldin et al., 2006]

The power of interaction [Wegner, 1997]

Interaction is a more powerful paradigm than rule-based algorithms for computer-based solving, overtiring the prevailing view that all computing is expressible as algorithms.

Complexity in Computational Systems III

Intelligence & interaction [Brooks, 1991]

Real computational systems are not rational agents that take inputs, compute logically, and produce outputs... It is hard to draw the line at what is intelligence and what is environmental interaction. In a sense, it does not really matter which is which, as all intelligent systems must be situated in some world or other if they are to be useful entities.

A conceptual framework for interaction [Milner, 1993]

... a theory of concurrency and interaction requires a new conceptual framework, not just a refinement of what we find natural for sequential [algorithmic] computing.

Interaction & Expressiveness I

Interactive computing [Wegner and Goldin, 1999]

- *finite computing agents* that interact with an environment are shown to be more expressive than Turing machines according to a notion of expressiveness that measures problem-solving ability and is specified by observation equivalence
- *sequential interactive models* of objects, agents, and embedded systems are shown to be more expressive than algorithms
- *multi-agent* (distributed) *models of coordination*, collaboration, and true concurrency are shown to be more expressive than sequential models

Interaction & Expressiveness II

Basically, where does complexity come from?

- events in a sequential component are *totally ordered*
- as soon as we combine components in a concurrent system (*distribution in time*), they are *no* longer totally *ordered*
- as soon as we combine components in a distributed system (*distribution in space*), interaction occurs in different contexts
- interaction make the overall system essentially *unpredictable*

! the range of behaviours that an interactive system can exhibit is typically larger than non-interactive systems

$\longrightarrow$ more behaviours means more expressiveness

Building Complex Computational Systems I

Interaction as a computational dimension

- *interaction* as a fundamental dimension for *modelling* and engineering complex computational systems
- for instance, a well-founded *theory of interaction* is essential to model *sociality* [Castelfranchi et al., 1993] and *situatedness* [Mariani and Omicini, 2015] in multi-agent systems (MAS)

Building Complex Computational Systems II

Compositionality, formalisability, expressiveness

- roughly speaking, when interaction within a system is (not) relevant, system properties cannot (can) be straightforwardly derived by component properties
- *compositional* vs. *non-compositional* systems
- computer scientists vs. computer engineers
- system *formalisability* vs. system *expressiveness*

e.g., interaction is the main source of *emergent social phenomena* in MAS [Castelfranchi, 1998]

Building Complex Computational Systems III

Interaction as a first-class issue

The *inter-disciplinary study of interaction* in many diverse scientific areas dealing with complex systems basically draws the foremost lines of *evolution* of contemporary *computational systems* [Omicini et al., 2006]

interaction — an essential and *independent dimension* of computational systems, *orthogonal to* mere *computation* [Gelernter and Carriero, 1992, Wegner, 1997]

environment — a *first-class abstraction* in the *modelling* and *engineering* of complex computational systems, such as pervasive, adaptive, and multi-agent systems [Weyns et al., 2007]

mediation — environment-based *mediation* [Ricci and Viroli, 2005] is the key to *designing* and *shaping* the *interaction space* within complex software systems, in particular socio-technical ones [Omicini, 2012]

middleware — provides complex socio-technical systems with the mediating abstractions required to *rule* and govern *social* and *environment interaction* [Viroli et al., 2007]

Next in Line...

Harnessing the Complexity of Interaction

- coordination is *managing interaction* [Wegner, 1997]
- coordination models work by *constraining* the space of interaction [Wegner, 1996]
- so, in principle, coordination abstractions and technologies can help *harnessing* the intricacies of interaction in the engineering of complex software systems

A Meta-model for Coordinated Systems I

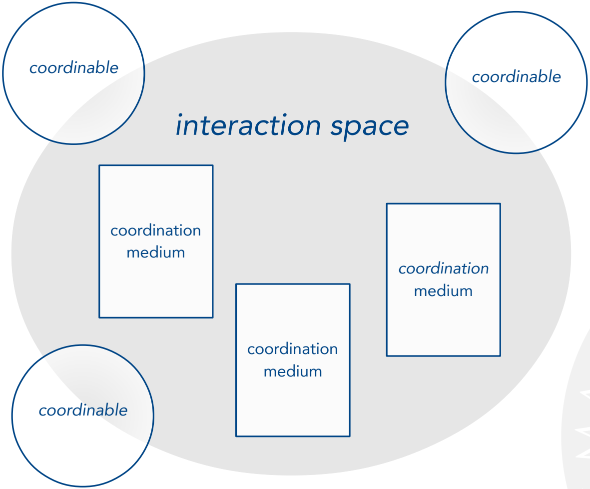
The coordination meta-model [Ciancarini, 1996]

coordination entities — the entities whose mutual interaction is ruled by the model, also called the *coordinables* (or, the *agents*)

coordination media — the abstractions enabling and ruling interaction among coordinables

coordination laws — the rules governing the observable behaviour of coordination media and coordinables, and their interaction as well

A Meta-model for Coordinated Systems II



A Meta-model for Coordinated Systems III

The coordination media...

- "fill" the interaction space
- enable / promote / govern the admissible / desirable / required interactions among the interacting entities
- according to some *coordination laws*
  - enacted by the behaviour of the media
  - defining the semantics of coordination

A New Perspective over Computational Systems

Programming languages

- interaction as an *orthogonal* dimension
- *languages* for interaction / *coordination*

Software engineering

- interaction as an *independent design* dimension
- coordination *patterns*

Artificial intelligence

- interaction as a new *source for intelligence*
- *social intelligence*

Next in Line...

Interaction in Physical Systems I

Independence from interaction

- some physical systems are described under the assumption of mutual independence among particles—that is, the behaviour of the particles is unaffected by their mutual interaction

  e.g., ideal gas [Boltzmann, 1964]

  - there, the probability distribution of the whole system is the product of those of each of its particles

- in computer science terms, the *properties of the system* can be compositionally derived by the *properties of the individual components* [Wegner, 1997]

→ neither macroscopic sudden shift nor abrupt change for the system as a whole: technically, those systems have *no phase transitions*—of course, while the "independence from interaction" hypothesis holds

Interaction in Physical Systems II

Interacting systems

- introducing interaction among particles structurally *changes* the *macroscopic properties*, along with the *mathematical* ones
- interacting systems are systems where particles *do not behave independently* of each other
- the probability distribution of an interacting system does not factorise anymore
- in computer science terms, an interacting system is *non-compositional* [Wegner, 1997]

From Physical to Social Systems I

Large numbers

- key point in statistical mechanics is to relate the *macroscopic* observables quantities – like pressure, temperature, etc. – to suitable *averages* of *microscopic* observables—like particle speed, kinetic energy, etc.
- based on the *laws of large numbers*, the method works for those systems made of a large number of particles / basic components

From Physical to Social Systems II

Beyond the boundaries

- *methods for complex systems* from statistical mechanics have expanded from physics to fields as diverse as biology [Kauffman, 1993], economics [Bouchaud and Potters, 2003, Mantegna and Stanley, 1999], and computer science itself [Mézard and Montanari, 2009, Nishimori, 2001]
- recently, they have been applied to *social sciences* as well: there is evidence that the complex behaviour of many observed socio-economic systems can be approached with the *quantitative tools* from statistical mechanics
  - e.g., *econophysics* for crisis events [Stanley, 2008]

From Physical to Social Systems III

Social systems as interacting systems

- a group of isolated individuals neither knowing nor communicating with each other is the typical example of a *compositional* social system
- no sudden shifts are expected in this case at the collective level, unless it is caused by strong external exogenous causes
- to obtain a *collective behaviour* displaying *endogenous* phenomena, the individual *agents* should 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
  - e.g., a simple *imitative* interaction is capable to cause strong polarisation effects even in presence of extremely small external inputs
- (non-trivial) *social systems as interacting systems*

Coordinated Systems as Interacting Systems I

Coordination media for ruling interaction

- defining the abstractions for ruling the interaction space in computational systems basically means to define their *coordination model* [Gelernter and Carriero, 1992, Ciancarini, 1996, Ciancarini et al., 1999]
- global properties of complex coordinated systems depending on interaction can be enforced through the coordination model, essentially based on its *expressiveness* [Zavattaro, 1998, Denti et al., 1998]
    - for instance, tuple-based coordination models have been shown to be expressive enough to support *self-organising coordination* patterns for nature-inspired distributed systems [Omicini, 2013]

Coordinated Systems as Interacting Systems II

The role of coordination models

Coordination models could be exploited

- to rule the interaction space
- so as to define new sorts of global, macroscopic properties for *computational systems*—possibly inspired by physical ones

Coordinated Systems as Interacting Systems III

Research perspectives

We need to understand

- how to relate methods from physics with coordination models
- whether physics notions such as *phase*, *phase transition*, or any other macroscopic system property could translate from statistical mechanics to computer science
- what such notions would imply for computational systems
- whether new, original notions could apply to computational systems
- which sort of coordination model could support such notions

Next in Line...

Socio-Technical Systems

Humans vs. software

- nowadays, a particularly-relevant class of *social systems* is represented by socio-technical systems (STS) [Whitworth, 2006]
- in STS
  - active components are mainly represented by *humans*
  - whereas interaction is almost-totally regulated by the *software infrastructure*
  - where *software agents* often play a key role
- this is the case, for instance, of *social platforms* like FaceBook [FaceBook, 2013] and LiquidFeedback [LiquidFeedback, 2013]

Physical & Computational Social Systems I

A twofold view of socio-technical systems

- the nature of STS is twofold: they are *both social systems and computational systems* [Verhagen et al., 2013, Omicini, 2012]
- as complex social systems, their complex behaviour is in principle amenable of mathematical modelling and prediction through notions and tools from statistical mechanics
- 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

Physical & Computational Social Systems II

Computational systems meet physical systems

- in STS, macroscopic properties could be
  - described by exploiting the conceptual tools from physics
  - enforced by the coordination abstractions
- STS could exploit both
  - the notion of complexity by statistical mechanics, along with the mathematical tools for behaviour modelling and prediction, and
  - coordination models and languages to suitably shape the interaction space

Physical & Computational Social Systems III

Vision

Complex socio-technical systems could be envisioned

- whose implementation is based on suitable coordination models
- whose macroscopic properties can be modelled and predicted by means of mathematical tools from statistical physics

thus reconciling the scientist and the engineer views over systems

First reading

paper [Omicini and Contucci, 2013]

presentation `http://www.slideshare.net/andreaomicini/complexity-interaction-blurring-borders-between-physical-computational-and-social-systems-preliminary-notes`

Next in Line. . .

Conclusion I

Interaction in complex systems

Interaction is key issue for complex systems

- *interacting systems* in physics
- *coordinated systems* in computer science
- *socio-technical systems* such as social platforms
  - e.g., FaceBook, LiquidFeedback

Conclusion II

The role of coordination models

- *coordinated systems* as interacting systems
- *coordination models* as the 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 systems

Case study

Socio-technical systems such as large social platforms could represent a perfect 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

Conclusion III

Next steps

We are currently experimenting with *digital democracy platforms* by exploiting

- *coordination technologies* for setting macroscopic system properties
- *statistical mechanics* tools for predicting global system behaviour

References I

Boltzmann, L. (1964).
Lectures on Gas Theory.
University of California Press.

Bouchaud, J.-P. and Potters, M. (2003).
Theory of Financial Risk and Derivative Pricing: From Statistical Physics to Risk Management.
Cambridge University Press, Cambridge, UK, 2nd edition.

Brooks, R. A. (1991).
Intelligence without reason.
In Mylopoulos, J. and Reiter, R., editors, *12th International Joint Conference on Artificial Intelligence (IJCAI 1991)*, volume 1, pages 569–595, San Francisco, CA, USA. Morgan Kaufmann Publishers Inc.

Castelfranchi, C. (1998).
Modelling social action for AI agents.
Artificial Intelligence, 103(1-2):157–182.

References II

Castelfranchi, C., Cesta, A., Conte, R., and Miceli, M. (1993).
Foundations for interaction: The dependence theory.
In Torasso, P., editor, *Advances in Artificial Intelligence*, volume 728 of *Lecture Notes in Computer Science*, pages 59–64. Springer Berlin Heidelberg.

Ciancarini, P. (1996).
Coordination models and languages as software integrators.
ACM Computing Surveys, 28(2):300–302.

Ciancarini, P., Omicini, A., and Zambonelli, F. (1999).
Coordination technologies for Internet agents.
Nordic Journal of Computing, 6(3):215–240.

Denti, E., Natali, A., and Omicini, A. (1998).
On the expressive power of a language for programming coordination media.
In *1998 ACM Symposium on Applied Computing (SAC'98)*, pages 169–177, Atlanta, GA, USA. ACM.
Special Track on Coordination Models, Languages and Applications.

FaceBook (2013).
Home page.
`http://www.facebook.com`.

References III

Gelernter, D. and Carriero, N. (1992).
Coordination languages and their significance.
Communications of the ACM, 35(2):97–107.

Goldin, D. Q., Smolka, S. A., and Wegner, P., editors (2006).
Interactive Computation: The New Paradigm.
Springer.

Kauffman, S. A. (1993).
The Origins of Order: Self-organization and Selection in Evolution.
Oxford University Press.

Kauffman, S. A. (2003).
Investigations.
Oxford University Press.

LiquidFeedback (2013).
Home page.
`http://liquidfeedback.org`.

References IV

Mantegna, R. N. and Stanley, H. E. (1999).
Introduction to Econophysics: Correlations and Complexity in Finance.
Cambridge University Press, Cambridge, UK.

Mariani, S. and Omicini, A. (2015).
Coordinating activities and change: An event-driven architecture for situated MAS.
Engineering Applications of Artificial Intelligence, 41:298–309.
Special Section on Agent-oriented Methods for Engineering Complex Distributed Systems.

Mézard, M. and Montanari, A. (2009).
Information, Physics, and Computation.
Oxford University Press, Oxford, UK.

Milner, R. (1993).
Elements of interaction: Turing award lecture.
Communications of the ACM, 36(1):78–89.

Nishimori, H. (2001).
Statistical Physics of Spin Glasses and Information Processing: An Introduction, volume 111 of *International Series of Monographs on Physics.*
Clarendon Press, Oxford, UK.

References V

Omicini, A. (2012).
Agents writing on walls: Cognitive stigmergy and beyond.
In Paglieri, F., Tummolini, L., Falcone, R., and Miceli, M., editors, *The Goals of Cognition. Essays in Honor of Cristiano Castelfranchi*, volume 20 of *Tributes*, chapter 30, pages 565–578. College Publications, London.

Omicini, A. (2013).
Nature-inspired coordination for complex distributed systems.
In Fortino, G., Bădică, C., Malgeri, M., and Unland, R., editors, *Intelligent Distributed Computing VI*, volume 446 of *Studies in Computational Intelligence*, pages 1–6. Springer.
6th International Symposium on Intelligent Distributed Computing (IDC 2012), Calabria, Italy, 24-26 September 2012. Proceedings. Invited paper.

Omicini, A. and Contucci, P. (2013).
Complexity & interaction: Blurring borders between physical, computational, and social systems. Preliminary notes.
In Bădică, C., Nguyen, N. T., and Brezovan, M., editors, *Computational Collective Intelligence. Technologies and Applications*, volume 8083 of *LNCS*, pages 1–10. Springer Berlin Heidelberg.
5th International Conference (ICCCI 2013). Craiova, Romania, 11–13 September 2013, Proceedings. Invited Paper.

References VI

Omicini, A., Ricci, A., and Viroli, M. (2006).
The multidisciplinary patterns of interaction from sciences to Computer Science.
In [Goldin et al., 2006], pages 395–414.

Ricci, A. and Viroli, M. (2005).
Coordination artifacts: A unifying abstraction for engineering environment-mediated coordination in MAS.
Informatica, 29(4):433–443.

Simon, H. A. (1962).
The architecture of complexity.
Proceedings of the American Philosophical Society, 106(6):467–482.

Stanley, H. E. (2008).
Econophysics and the current economic turmoil.
American Physical Society News, 17(11):8.
The Back Page.

Verhagen, H., Noriega, P., Balke, T., and de Vos, M., editors (2013).
Social Coordination: Principles, Artefacts and Theories (SOCIAL.PATH), AISB Convention 2013, University of Exeter, UK. The Society for the Study of Artificial Intelligence and the Simulation of Behaviour.

References VII

Viroli, M., Holvoet, T., Ricci, A., Schelfthout, K., and Zambonelli, F. (2007).
Infrastructures for the environment of multiagent systems.
Autonomous Agents and Multi-Agent Systems, 14(1):49–60.
Special Issue: Environment for Multi-Agent Systems.

Wegner, P. (1996).
Coordination as constrained interaction.
In Ciancarini, P. and Hankin, C., editors, *Coordination Languages and Models. First International Conference, COORDINATION '96 Cesena, Italy, April 15–17, 1996. Proceedings*, Lecture Notes in Computer Science, pages 28–33, Cesena, Italy. Springer Berlin Heidelberg.

Wegner, P. (1997).
Why interaction is more powerful than algorithms.
Communications of the ACM, 40(5):80–91.

Wegner, P. and Goldin, D. (1999).
Mathematical models of interactive computing.
Technical report, Brown University, Providence, RI, USA.

References VIII

Weyns, D., Omicini, A., and Odell, J. J. (2007).
Environment as a first-class abstraction in multi-agent systems.
Autonomous Agents and Multi-Agent Systems, 14(1):5–30.
Special Issue on Environments for Multi-agent Systems.

Whitworth, B. (2006).
Socio-technical systems.
In Ghaou, C., editor, *Encyclopedia of Human Computer Interaction*, pages 533–541. IGI Global.

Zavattaro, G. (1998).
On the incomparability of Gamma and Linda.
Technical Report SEN-R9827, CWI, Amsterdam, The Netherlands.

Complexity in Computational Systems: The Coordination Perspective

Andrea Omicini
andrea.omicini@unibo.it

Dipartimento di Informatica – Scienza e Ingegneria (DISI)
Alma Mater Studiorum – Università di Bologna a Cesena

Complex Systems Physics / IMT-UniBo
Bologna, Italy, 15 February 2018