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

## Preliminary Notes

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1. Interaction & Complex Systems
   - Complexity
   - Computational Systems
   - Physical Systems
   - Social Systems
2. Perspectives
   - Coordination Models
   - Socio-technical Systems
3. Final Remarks

# Outline

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# Complexity as a Multi-disciplinary Notion

## Complex systems everywhere

- 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

## Natural vs. artificial complex systems

- We *observe* and *model* complex physical systems
- We *design* and *build* complex computational systems

## Question

- Which features do *all* complex systems share independently of their nature?

# Complexity & Interaction

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

## Laws of complexity

- Some "laws of complexity" exists that characterise any complex system, *independently* of its specific nature [Kauffman, 2003]
- The precise source of what all complex systems share is still unknown in essence

## Interaction

- We argue that interaction – its *nature*, *structure*, *dynamics* – is the key to understand some fundamental properties of complex systems of any kind

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# Interaction in 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, 2013] in multi-agent systems (MAS)

# Interaction in Complex (Computational) Systems II

## Interaction as a source of complexity

- Interaction is the most relevant source of complexity for computational systems nowadays [Wegner, 1997]
  - 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*
- For instance, interaction is the main source of *emergent social phenomena* in MAS [Castelfranchi, 1998]

# Interaction in 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]

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# Interaction in Statistical Mechanics 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 Statistical Mechanics 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]

# Interaction in Statistical Mechanics III

## Interacting vs. non-interacting systems

- Only interacting systems can describe real cases beyond the idealised ones
  - e.g., they can 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*

# Complexity in Statistical Mechanics I

## The case of magnetic particles

- 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 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 in Statistical Mechanics II

## Interaction is not enough

- Interaction is a necessary ingredient for complexity in statistical mechanics but definitely not a sufficient one
- 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
- Roughly speaking, complexity is much more related to size in number, rather than to complexity of the laws ruling interaction

→ we do *not* need *complex interaction* to make interaction lead to complexity

- In the so-called mean field *theory of spin glasses* [Mézard et al., 1986], particles do not just interact, but are alternatively either *imitative* or *anti-imitative* with the same probability [Contucci and Giardinà, 2012]
- Both prototypical cooperation and competition effects can be observed, and the resulting emerging collective effect is totally new

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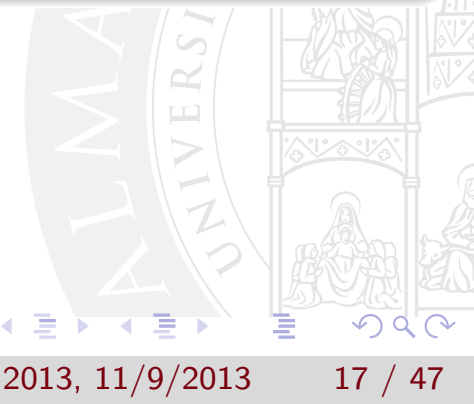
# From Statistical Mechanics to Social Systems I

## Large numbers

- The 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 Statistical Mechanics 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 Statistical Mechanics to Social Systems III

## Social systems as statistical mechanical 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

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# Computational Systems as Interacting Systems

## Physical vs. computational systems

- Physical systems are to be observed, understood, and possibly *modelled*
  - → 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
- Computational systems are to be *designed* and built
  - → For computational 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 build systems

# A Meta-model for Coordinated Systems I

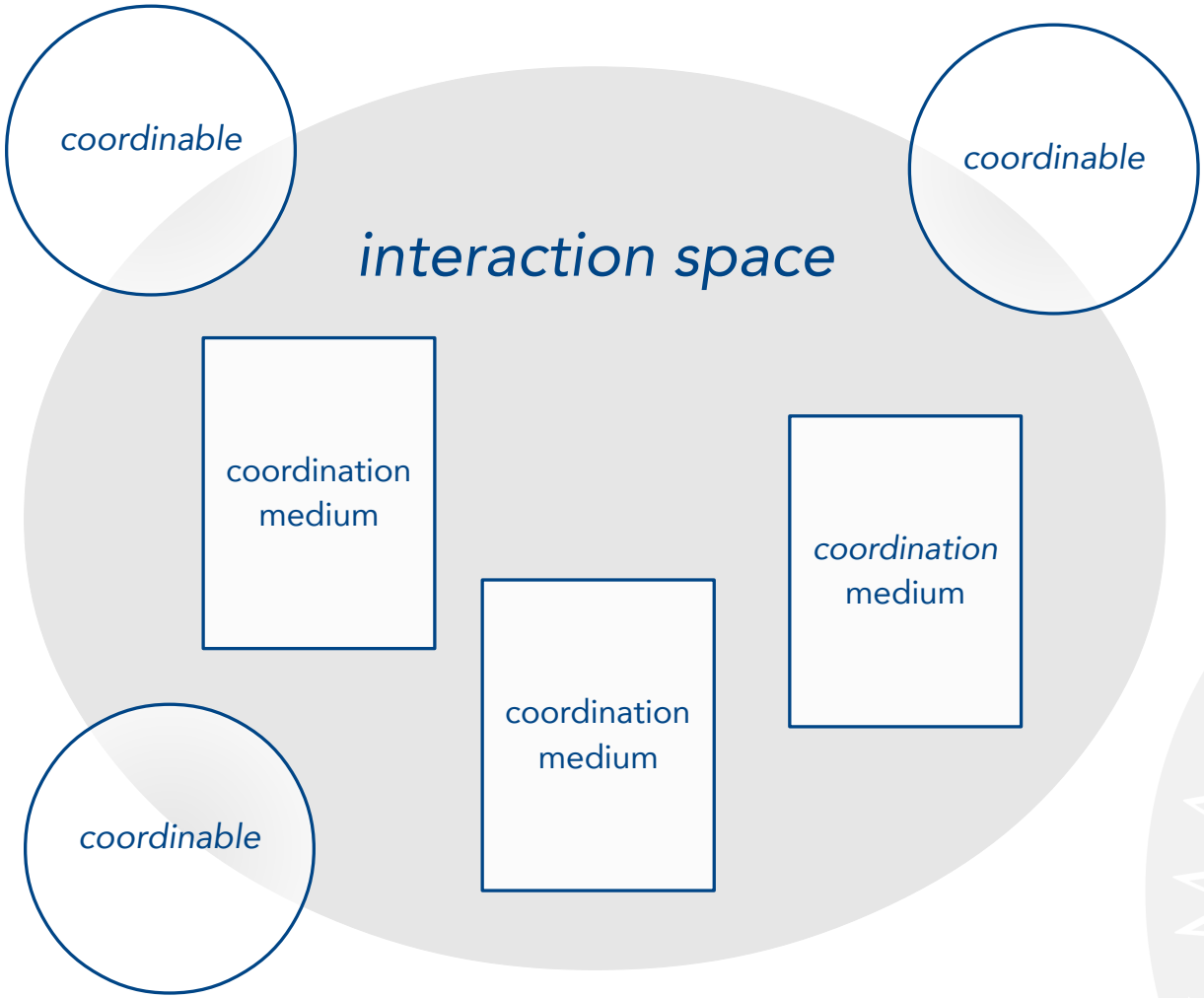
## The coordination meta-model [Ciancarini, 1996]

**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 medium of coordination...

- "fills" the interaction space
- enables / promotes / governs the admissible / desirable / required interactions among the interacting entities
- according to some *coordination laws*
  - enacted by the behaviour of the medium
  - defining the semantics of coordination

# 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 statistical mechanics with coordination models
- whether notions such as *phase*, *phase transition*, or any other macroscopic system property, could be transferred 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

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# Socio-Technical Systems

## Humans vs. software

- Nowadays, a particularly-relevant class of *social systems* is represented by socio-technical systems
- In socio-technical systems
  - 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 socio-technical systems 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 socio-technical systems, macroscopic properties could be
  - described by exploiting the conceptual tools from physics
  - enforced by the coordination abstractions
- Socio-technical systems 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

We envision complex socio-technical systems

- 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.

# 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

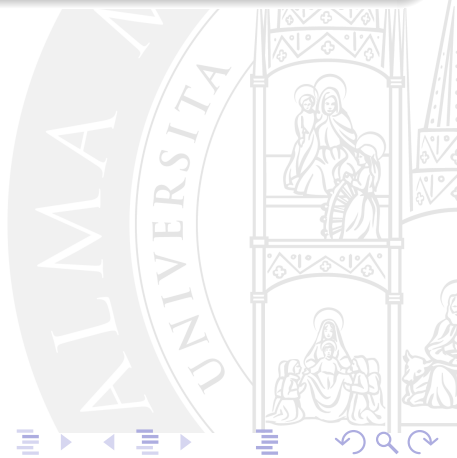
Socio-technical systems such as large social platforms could represent a perfect case study for the *convergence* of the ideas and tools from *statistical mechanics* and *computer science*, being both social and computational systems at the same time

# Conclusion III

## Next steps

We plan to experiment with social platforms like FaceBook and LiquidFeedback, by exploiting

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



# Further References

## Paper

Reference [Omicini and Contucci, 2013]

APICe `http://apice.unibo.it/xwiki/bin/view/Publications/InteractioncomplexityIccci2013`

## Presentation

APICe `http://apice.unibo.it/xwiki/bin/view/Talks/InteractioncomplexityIccci2013`

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

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# 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.

Castelfranchi, C. (1998).

Modelling social action for AI agents.

*Artificial Intelligence*, 103(1-2):157–182.

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.

# References II

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.

Contucci, P. and Giardinà, C. (2012).
*Perspectives on Spin Glasses*.
Cambridge University Press, Cambridge, UK.

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.

# References III

FaceBook (2013).

Home page.

http://www.facebook.com.

Gelernter, D. and Carriero, N. (1992).

Coordination languages and their significance.

*Communications of the ACM*, 35(2):97–107.

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.

# References IV

LiquidFeedback (2013).

Home page.

http://liquidfeedback.org.

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. (2013).

Event-driven programming for situated MAS with ReSpecT tuple centres.

In Klusch, M., Thimm, M., and Paprzycki, M., editors, *Multiagent System Technologies*, volume 8076 of *LNAI*, pages 306–319. Springer.

11th German Conference (MATES 2013), Koblenz, Germany, 16-20 September 2013. Proceedings.

Mézard, M. and Montanari, A. (2009).

*Information, Physics, and Computation*.

Oxford University Press, Oxford, UK.

# References V

Mézard, M., Parisi, G., and Virasoro, M. A. (1986).

*Spin Glass Theory and Beyond. An Introduction to the Replica Method and Its Applications*, volume 9 of *World Scientific Lecture Notes in Physics*.

World Scientific Singapore.

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.

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 29, pages 543–556. College Publications, London.

# References VI

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 VII

Omicini, A., Ricci, A., and Viroli, M. (2006).

The multidisciplinary patterns of interaction from sciences to Computer Science.

In Goldin, D. Q., Smolka, S. A., and Wegner, P., editors, *Interactive Computation: The New Paradigm*, pages 395–414. Springer.

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.

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# References VIII

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.

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. (1997).

Why interaction is more powerful than algorithms.

*Communications of the ACM*, 40(5):80–91.

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.

# References IX

Zavattaro, G. (1998).

On the incomparability of Gamma and Linda.

Technical Report SEN-R9827, CWI, Amsterdam, The Netherlands.

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