Emergence in Organic Computing Systems: A Controversial Issue

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Introduction – 1

Why are we interested in emergence?

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"The priority research program [...] addresses fundamental challenges in the design of Organic Computing systems; its objective is a deeper understanding of **emergent** *global behavior in self-organizing systems and the design of specific concepts and tools to support the construction of Organic Computing systems for technical applications."*

... taken from our OC website.

Introduction – 2

Objectives of this talk:

- Overview of various notions of the term "emergence"
- Assessment of these notions from the viewpoint of OC

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Introduction – 3

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In **computer science** and **engineering**, emergent behavior of "intelligent" technical systems is studied since a few years.

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Introduction – 3

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Require emergent phenomena in computer science and in philosophy of mind different notions of emergence?

Examples for interesting questions:

- In philosophy: Why and how does *human experience* arise?
- In computer science: How can *unexpected behavior of multi-agent systems* be characterized, measured, and / or controlled?

Agenda

- Introduction
- Notions of emergence in philosophy of mind
- Notions of emergence in computer science and engineering
- Conclusion

Remarks

First, we will take a look at various historical (philosophical) definitions of emergence and discuss whether they are useful from the viewpoint of OC.

These historical definitions are adopted from a book on emergence, written by **Achim Stephan**, Institute of Cognitive Science, University of Osnabrück, Germany.

Weak Emergentism – 1

Weak emergentism:

- Is based on the following three theses:
  - **thesis of physical monism**
  - **thesis of systemic (collective) properties**
  - **thesis of synchronous determinism**
- Is the basis for higher grades of emergentism – those can be defined by adding new requirements (i.e., theses).

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Weak Emergentism – 2

Thesis of physical monism:

- Restricts the type of components of complex systems with emergent properties.
- Says: **All systems – including those systems that have emergent properties – consist of physical entities.**
- In particular, it says that there are no supernatural influences.
- Has some historical importance (debate vitalism vs. mechanism).

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Weak Emergentism – 3

Thesis of systemic (collective) properties:

- Characterizes the type of properties that are candidates for being termed emergent properties.
- Says: **Emergent Properties are collective (systemic), i.e., the system as a whole has this property but single components do not have properties of this type.**
- Often cited this way: "The whole is more that the sum of its parts."

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Weak Emergentism – 4

Thesis of synchronous determinism:

- Specifies the relation between the "microstructure" of a system and its emergent properties.
- Says: **Emergent properties of a system depend on its structure and the properties of components in a nomological way.**
- In particular, it says that there is no difference in systemic properties without changes in the structure of the system, changes of the properties of the components, or the like.

Weak Emergentism – 5

Examples for systems that have **emergent properties in this weak sense**:

- *Artificial Neural Networks*: combinations of simple nodes and connections can be used for pattern matching problems
- *Mineralogy*: carbon atoms build up materials of different hardness – depending on the type of the crystal lattice (e.g. graphite vs. diamond)
- *Electronics*: components such as a resistor, an inductor, and a capacitor build a resonant circuit
- *Artificial Life*: swarms of artificial animals, e.g. birds (boids), are able to avoid obstacles
- *Thermodynamics*: Bénard's convection cells (system with dissipative structures)
- ...

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Weak Emergentism – 6

Conclusion:

- "The whole is more that the sum of its parts." is less than weak emergence. The thesis of systemic (collective) properties claims that single components do not have **properties of the same type**.
- *OC viewpoint: Weak emergence is a necessary pre-condition, but not sufficient. Only the thesis of systemic properties is relevant.*
- There are many systems that are emergent in this weak sense but their emergent properties are not really interesting.

Strong Emergentism – 1

In philosophy of mind, a notion of emergence that adds very stringent requirements to weak emergence is **strong emergence**.

Strong emergentism (synchronous emergentism)

- Is based on the **thesis of irreducibility**.
- Can be regarded as the “highest” grade of emergentism.

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Strong Emergentism – 2

Thesis of irreducibility:

- Addresses the question why a system has a certain property.
- Says: **A systemic property of a system is irreducible if one of the following conditions hold:**
  - **As a matter of principle, it does not arise from the behavior, the properties, and the structure of components.**
  - **As a matter of principle, it does nor arise from the properties that the components show either in isolation or in other configurations.**
- In the case of strong emergence, a **reductive explanation** does not exist and will never be found.

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Strong Emergentism – 3

Many systems that we would call emergent are certainly not emergent in this **strong** sense:

- *ANN*: pattern recognition capabilities can be explained knowing a network architecture, weights of connections, etc.
- *A-Life*: swarm behavior of boids can be explained knowing some simple interaction rules
- *Electronics*: the behavior of a resonant circuit can be explained by means of differential equations
- ...

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Strong Emergentism – 4

Conclusion:

- "The macro behavior of a system can **in principal** not be explained knowing the micro behavior of components, their interaction rules etc." is strong emergence.
- *OC viewpoint: The notion of strong emergence does not help because artificial technical systems are not emergent in a strong sense.*

  There is often only a so-called explanatory gap:
  - *We do not have the knowledge to explain expected behavior in advance or to describe an observed behavior.*
  - *We did not specify the components or systems that we investigate in a sufficiently detailed way.*
  - *...*
- It is mind-boggling whenever complex behavior on the system level follows from very simple rules on the components level or the like.

Between Weak and Strong Emergentism

From the viewpoint of technical systems, traditional **philosophical definitions of emergence** are either to weak or to strong.

The former means that too many systems are regarded as emergent, the latter implies that almost no artificial (technical) systems can can be seen as emergent.

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However, it makes sense not to neglect historical philosophical approaches.

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Remarks – 1

So what?

- We need various notions of emergence (weak emergence + ε) depending on the type of technical systems we investigate and, possibly, the type of questions we ask.
- Again, there have been various attempts in the past ...

In the following, we will set out some alternative notions of emergence that are certainly important from the viewpoint of OC.

Remarks – 2

The thoughts reflected in the following have been published in 2005 or 2006 by

- **Giovanna Di Marzo Serugendo**, **Marie-Pierre Gleizes**, and **Anthony Karageorgos**
- **Russ Abbott**
- **Achim Stephan**
- **Jochen Fromm**
- **Tom De Wolf** and **Tom Holvoet**
- **Christian Müller-Schloer**

Fundamental Findings – 1

Giovanna Di Marzo Serugendo et al. call the historical notion **proto-emergentism** to distinguish it from a technical-oriented **neo-emergentism** that deals with systems that are less “miraculous”.

That is, an artificial system can also be regarded as emergent if its behavior can be understood and reproduced at least to a certain degree.

In their opinion, **designable emergence** occurs in a narrow “space lying between conditions that are too ordered and too disordered.”

Fundamental Findings – 2

Ross Abbott distinguishes the following types of emergence:

- **static emergence** – realization does not depend on time (e.g., hardness of a material)
- **dynamic emergence** – defined in terms of how a system changes over time (e.g., due to self-organization)
  - non-stigmergic dynamic phenomena: can be defined by means of continuous equations
  - stigmergic dynamic phenomena: involve autonomous entities that may have discrete states

Stigmergic dynamic emergence is certainly most interesting from the viewpoint of OC.

Explanation-Oriented Notion of Emergence – 1

Achim Stephan specifies various types of emergence depending on the rationale for an emergent behavior.

Emergence in the sense of collective self-organization

- Reason: In many cases, interesting properties at the system level (e.g., certain communication patterns) are realized by interaction of identical or similar components.
- Example: Systems, e.g., in robotics that behave such as ant colonies.

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Explanation-Oriented Notion of Emergence – 2

Emergence in the sense of non-programmed functionality

- Reason: Many systems that interact with their environment show a certain goal-oriented, adaptive behavior that is not a result of dedicated control processes or explicit programming.
- Example: A robot creating heaps of candles by following rules that only address the way of movement.

Emergence in the sense of interactive complexity

- Reason: Many interesting systemic properties, patterns, or processes are the result of a complex interaction of components.
- Example: A distributed system in which nodes exchange information with autonomously chosen partners at any point in time they want.

Explanation-Oriented Notion of Emergence – 3

Emergence in the sense of unpredictability

- Reason: There are many systems where the formation of new properties, patterns, or structures follows the laws of **deterministic chaos** and where it is unpredictable in this sense.
- Examples: Population model where the growth rate is not constant but depends on the population size.

Emergence in the sense of incompressible development

- Reason: The idea is that a system is called emergent if a macrostate of that system with a certain microdynamic can be derived from the microdynamics and the system's external conditions but only by simulation.
- Examples: **John Horton Conway**'s Game of Life.

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Modeling-Oriented Notion of Emergence – 1

Jochen Fromm's taxonomy of the key types and forms of emergence in multi-agent systems:

- **Class I** deals with **nominal emergence** that is either intended or not.

  Examples:
  - planned function of a machine is an emergent property of the machine components
  - properties of a (large) number of identical particles or molecules such as pressure or temperature

- **Class II** comprises systems with top-down feedback that may lead to stable or instable forms of **weak emergence**.

  Examples:
  - flocks of animals that interact directly or indirectly
  - emergent behavior due to self-organization in open source software projects

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Modeling-Oriented Notion of Emergence – 2

- **Class III** includes systems with multiple feedback, e.g. short-term and long-term feedback (**multiple emergence**).

  Examples:
  - stock market with many feedback mechanisms yielding sometimes oscillating or chaotic behavior
  - ecological system with catastrophic events influencing evolution by accelerating adaptation

- **Class IV** contains systems exhibiting **strong emergence**. Strong emergence is "related to very large jumps in complexity and major evolutionary transitions".

  Examples:
  - emergence of life on earth
  - emergence of culture

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Emergence and Self-Organization

Tom De Wolf and **Tom Holvoet** discuss the relationship of emergence and **self-organization**. Both can, according to the authors, exist in isolation or together.

From an OC viewpoint, these two concepts seem to be highly related: Emergence typically is the result of an adaptive, mostly self-organizing (in the broadest sense) process.

Measurement-Oriented Notion of Emergence

Christian Müller-Schloer deals with emergence as a result of self-organizing processes and measures emergence gradually.

Measure for emergence: **entropy**

In a particular application, the challenge is to find appropriate attributes of the process that allow this kind of analysis.

Conclusion – 1

People are talking both about how to design or how to “do” emergence and how to cope with it, that is, how to control it!

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Is emergence in OC systems somehow a result of a so-called "meet-in-the-middle" design approach?

- We specify systems in a way such that we can expect a certain type of emergent behavior.
- Having some assumptions about this type of behavior, we are able to assess and to control it.

Conclusion – 2

In OC, emergence is typically the result of a self-organizing process (i.e., it is dynamic emergence).

We certainly need

- an explanation-oriented and a modeling-oriented view in order to design emergent OC systems and
- an analysis-oriented and measurement-oriented view in order to cope with emergent OC systems.

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Conclusion – 3

Thanks a bunch for your attention!