ComPlexUs
BIO INSPIRED METHODS
Complexus 2006;3:24–31 DOI: 10.1159/000094185

Elements about the Emergence Issue: A Survey of Emergence Definitions

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Key Words
Emergence · Complexity · Level definition

Abstract

Emergence, a concept that first appeared in philosophy, has been widely explored in the domain of complex systems and is sometimes considered to be the key ingredient that makes 'complex systems' 'complex'. Our goal in this paper is to give a broad survey of emergence definitions, to extract a shared definition structure and to discuss some of the remaining issues. We do not know of any comparable surveys about the emergence concept. For this presentation, we start from a broadly applicable approach and finish with more specific propositions. We first present five selected works with a short analysis of each. We then propose a merged analysis in which we isolate a common structure through all definitions but also what we think needs further research. Finally, we briefly describe some perspectives about the emergence engine idea also referred to as emergent engineering.

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Simplexus

What is 'emergence'? Individual ants within a colony have limited skills, yet somehow, through their interactions, intelligence 'emerges' at the collective level of the entire colony. The colony possesses an adaptive capability and resilience that individual ants do not. Likewise, out of the interactions of electrons in high-temperature superconductors, coherent magnetic vortices often emerge that follow laws entirely distinct from the basic physics of electrons themselves. In biology and economics, in the study of technological systems, and in physics and chemistry, 'emergence' is the phenomenon by which wholes become 'more than the sum of their parts'. But what is emergence – really?

As Deguet and colleagues point out in this essay, the notion of emergence first received attention in philosophy, but is nowadays 'owned' by the science of 'complex systems', where it tends to be used in a loose, descriptive sense. Can its meaning be pinned down more specifically? In this essay, the authors address this question by comparing several representative works that have attempted to define emergence. The definitions they consider can be summarized as follows:

(1) In describing a system, we generally try to identify features that capture important characteristics in some efficient way. It may be through 'eyeballing' the system, for example, to recognize a pattern, or by running some sophisticated algorithm. In any case, we identify important features by way of 'detectors' of some sort that either find the relevant features or do not. Given this (rather abstract) perspective, emergence can then be defined to take place at the moment when some detector finds some new feature that makes the overall description of the system simpler than it was before. For example, at the moment we notice ('detect') that a collection of water molecules flows as a fluid, we simplify its description considerably. In this view, emergence in-

1 Introduction

Emergence, a concept that first appeared in philosophy [1,2], has been widely explored in the domain of complex systems [3–10] and is sometimes considered to be the 'key ingredient that makes complex systems complex' [11].

On March 9, 2005, we did a basic one-key word Internet search for 'emergence' papers on computer science-specific engines and generalist scientific engines. We retrieved impressive amounts of relevant documents (table 1).

Table 1. Relevant documents found

Search engine	Number of results
ACM	648
IEEE	1,450
CiteSeer	8,257
ScholarGoogle	372,000

From these, we chose to survey five works matching the following criteria:

- Emergence definition is the primary goal.
- It contains a significantly different (and possibly contradictory) approach from other selected papers.

We chose not to give any introductory example or vague intuition here because it might fall out of the scope of a particular approach. Our goal in this paper is to give a broad survey of emergence definitions, to extract a shared definition structure and to discuss some of the remaining issues. We do not know of any comparable surveys about the emergence concept.

In this paper, we start from a broadly applicable approach and finish with more specific propositions. We first present five selected works with a short evaluation of each. We then propose a merged analysis in which we isolate a common structure through all definitions but also what we think needs further research. Finally, we briefly describe some perspectives about the emergence engine idea also referred to as emergent engineering.

2 Elements from Existing Definitions

2.1 Detection and Emergence

2.1.1 Concept

The first idea about emergence we present is the work of Bonabeau and Dessalles [7]. As the title suggests, the authors give significant importance to the detection of the phenomenon in their proposition:

> 'We propose here a conceptual framework, based on the notion of detection ... Then we show that emergence is related to complexity shifts. Lastly, we propose to focus on the observer, rather on the emerging system, in order to show that all characterizations of emergence are implicitly connected to the notion of detection.'

Given the two following notions:

detector defined as 'any device which gives a binary response to its input'

relative complexity $C(S|D,T)$ of a system S 'where D is a set of detectors and T a set of available tools that allow to compute a description of structures detected through D' which corresponds to the difficulty to describe the system given T and D.

Emergence happens when between time t and $t + \Delta t$, two events happen:

(1) A detector D_k becomes activated.

(2) $C_{t+\Delta t}(S|T,D_1,...,D_{k-1},D_k) <$
$C_t(S_\Delta T,D_1,...,D_{k-1})$.

This property is likely to happen in a hierarchy of detectors as they point out: 'When a detector becomes active in such a hierarchy, the active detectors from the lower level that are connected to it can be omitted from the description ... Emergence is thus a characteristic feature of detection hierarchies.'

2.1.2 Discussion

One widely shared feature of emergence definitions is the existence of levels. This definition is interesting because it defines emergence as internal to an observation involves the appearance of features that make description simpler.

(2) A second definition centres on the languages used to describe a system. A designer may use one language (L_1) to describe the interactions between some set of basic elements, yet another distinct language (L_2) may turn out to be more useful in describing their overall behaviour. This generally happens because L_2 has terms that refer to coherent entities which have no name in the lower language L_1. So the emergent process makes the new language both necessary and useful. [The authors suggest that this definition is limited to artificial systems where the idea of 'design' makes sense, but it might also be considered more generally. The lower level language L_1 might be natural for description at one level (say, atomic physics), but be replaced by a more suitable language at another level (say, chemistry).]

(3) A third definition focuses on simulation, and on the idea that emergent order cannot be linked in any 'obvious' way to a system's lower level parts. In this view, truly emergent features can only be explored and studied on the basis of simulation (by way of computation, for example, or by letting the system 'simulate' itself by running forward in time), and it is this difficulty that essentially identifies the features as emergent. The authors formalize this idea by saying that a phenomenon is emergent if the amount of computation, $s(n)$, required to produce it cannot be reduced by any 'deeper' understanding or 'shortcuts' of any kind.

(4) A fourth idea holds that emergence creates the possibility of 'downward causation'; that is, that emergent features gain a degree of autonomy from lower levels, and, because of that autonomy, explanations of what happens at lower levels may sometimes have to refer to events at the emergent level.

(5) Finally, a fifth definition suggests that emergence is intimately linked to a transition between 'formal grammars',

device that must be hierarchically organized. The authors do not assume levels a priori in the definition but show that this is a condition sine qua non for the complexity discontinuity to happen.

No assumption is made about the system under detection; therefore, one can apply this criterion to both artificial and natural systems as long as detection is possible.

This defines a low-to-high level emergence.

2.2 The Emergence Test

2.2.1 Concept

The first definition focused on an observer modelled by a detection apparatus. This makes emergence somehow 'subjective' as the complexity measure depends on this apparatus. However, once the observer is defined, emergence only depends on the perceived behaviour. The emergence test introduces the consideration of the system's design in addition to its behaviour, and therefore moves subjectivity out of the very domain of observation.

Explicitly inspired by Turing's test for intelligence [12], Ronald and colleagues [13, 14] proposed to define an 'emergence tag gun' instead of a formal definition.

This emergence test involves a system designer and a system observer (both of whom can in fact be one and the same). Then if the following three conditions hold, the emergence tag is conferred:

Design. The system has been constructed by the designer by describing local elementary interactions between components in a language L_1.

Observation. The observer is fully aware of the design, but describes global behaviour and properties of the running system, over a period of time, using a language L_2.

Surprise. The language of design L_1 and the language of observation L_2 are distinct, and the causal link between the elementary interactions programmed in L_1 and the behaviours observed in L_2 is non-obvious to the observer, who therefore experiences surprise. In other words, there is a cognitive dissonance between the observer's mental image of the system's design stated in L_1 and his contemporaneous observation of the system's behaviour stated in L_2.

They describe this question as reposing on how easy it is for the observer to bridge the gap between L_1 and L_2.

2.2.2 Discussion

We think we can consider Bonabeau and Dessalles' *D* and *T* as words and syntax of an observation language L_2.

The introduction of the design language L_1 has two important consequences:

(1) Emergence happens between the design and the observation. This defines a design-to-behaviour emergence.

(2) Existence of L_1 restricts the application of this criterion to artificial systems, i.e. designed by the human hand.

Emergence happens when observation and design appear loosely coupled to the observer. Therefore, the result of one 'tag gun' might differ from another, and the resulting emergence is highly subjective.

This corresponds to Baas' deducible emergence [15] where two disjoint levels are linked by a computational process. Indeed, Baas defines Obs^2 (similar to L_2), the 'new observational' mechanisms with respect to the observation mechanisms Obs^1 (that are part of L_1) used in the dynamics.

In the field of decentralized artificial intelligence, Demazeau and Müller [16] made a similar distinction between internal and external descriptions of agents where internal description refers to the real architecture of an agent and external description refers to its externally perceived behaviour.

2.3 Simulation Emergence

2.3.1 Concept

Making the parallel between intelligence and emergence as subjective notions defined by tests can lead to controversy. One answer could be to consider that emergence happens when a large number of sci-

logical structures that might be used to describe it. The idea is that an emergent system is 'more than the sum of its parts' in a very specific way: any language used to describe the whole system is inherently richer than the mere 'superposition' of languages suitable for describing the parts themselves.

The authors argue that a key element tying all these definitions together is the notion of 'levels'. Definitions of emergence may focus on detecting new features, describing them efficiently, or understanding them theoretically, but in every case distinct levels become important. Emergence demands attention because, when it is important, observation or description at a single level is generally inadequate. Descriptions at the 'micro-level' miss crucial emergent features; description at the 'macro-level' capture those features, but dismiss micro-level events that nevertheless have the potential to percolate upward to affect the larger world. An effective description of an ant colony cannot be a description of ants or collective colony function along. It requires thinking that stretches between two levels, somehow integrating the micro-level behaviour of ants with the larger functions to which they give rise.

In this regard, the authors mention one particularly interesting point (proposed by Bedau) that the relationship between the 'levels' of emergence rests on the remarkable possibility that two seemingly contradictory statements can be simultaneously true:

(A) Emergent phenomena depend on underlying processes.

(B) Emergent phenomena are autonomous from underlying processes.

Understanding this paradox seems to strike at the heart of the challenge of emergence.

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entists agree that it does. Another answer is to make the definition objective. Simulation emergence is such an attempt, focused on the simulation domain.

In Darley [17] we find this definition:

> 'A true emergent phenomenon is one for which the optimal means of prediction is simulation.'

The author defines two means of prediction depending on *n* the size of a system:

- $s(n)$: the optimal 'amount of computation required to simulate a system, and arrive at a prediction of the given phenomenon'.
- $u(n)$: stands for 'deeper level of understanding', the way we try to avoid computation by 'a creative analysis', $u(n)$ is the amount of computation required by this method.

Then the system will be considered as emergent if $u(n) \geq s(n)$, i.e. direct simulation is optimal relative to the 'amount of computation' measure. When decomposed into 'steps' the amount of computation is defined as the sum over steps of Kolmogorov complexities.

We link this definition with the weak emergence from Bedau [18, 19]:

> 'A macro-state *P* of *S* with micro-dynamic *D* is weakly emergent if *P* can be derived from *D* and *S*'s external conditions but only by simulation. ... for *P* to be weakly emergent, what matters is that there is a derivation of *P* from *D* and *S*'s external conditions and any such derivation is a simulation.'

2.3.2 Discussion

First, Bedau describes a new relation namely the micro-to-macro one, the macro-level being composed of micro-entities. We believe we can join this micro-to-macro emergence with the low-to-high one (see 2.1.1) without a loss of sense.

The key issue is to understand what a simulation is. Among all the ways to derive the phenomenon in a computable manner, some are simulations, others are 'shortcuts'. Then optimality of simulation is equivalent to the absence of 'shortcuts'; this is why we decided to present the two definitions together.

Interpreted in the L_1 L_2 framework, this states an irreducible gap between the language of design L_1 and observation L_2 which is optimally filled by going into all details of the system's evolution (i.e. simulation). We note that the emergence 'tag gun' used the size of the gap ('ease to bridge'); here the size itself does not matter.

An interesting point is that both authors address the question of decidability of emergence:

- In Bedau's formulation: 'One might worry that the concept of weak emergence is fairly useless since we generally have no proof that a given macrostate of a given system is underivable without simulation.'
- In Darley's words: 'Can we determine, for a given system, whether or not it is emergent?'

Darley suggests that 'for any complex system which is capable of universal computation, we know that the best (only) means of prediction in such a situation is to run the program i.e. perform the simulation'. Bedau notes that we usually 'possess substantial empirical support' to assess that it is so. Then, even if we have gained in objectivity, we might have encountered an undecidable criterion based on the definition of the simulation.

If we reformulate as 'the global behaviour is optimally obtained by running a system made of interacting micro agents', it provides a natural way to apply the definition to multi-agent-based simulations.

This definition might not apply out of the simulation domain[1].

2.4 Downward Causation and Emergence

2.4.1 Concept

Bedau has defined weak emergence with respect to the strong emergence based on downward causation. This view is illustrated by O'Connor [20]:

> '... to capture a very strong sense in which an emergent's causal influence is irreducible to that of the micro-properties on which it supervenes; it bears its influence in a direct downward fashion, in contrast to the operation of a simple structural macro-property, whose causal influence occurs via the activity of the micro-properties which constitutes it.'

Sawyer [21] notes that:

> 'In MAS and Alife social simulations, the emergent pattern is fully explained by the microsimulation; that is, reduced to an explanation in terms of agents and their interactions. Such reductionist assumptions imply that higher-level emergent patterns do not have any causal force.'

In order to achieve downward causation, he proposes that:

(1) 'As in blackboard systems, the emergent frame must be represented as a data structure external to all of the participating agents.'

(2) 'All emergent collective structures must be internalized by each agent, resulting in an agent-internal version of the emergent.'

(3) 'This internalization process is not deterministic and can result in each agent having a slightly different representation.'

2.4.2 Discussion

The question here is the possibility of downward causation.

We believe that L_1 and L_2 are of significant interest to clarify this issue. It sounds natural to us to consider that everything with causal powers in an artificial system lies in the L_1 design language as it must live within algorithm. Thus even if a data structure exists out of the agents at a macro-lev-

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[1] Perhaps an adaptation to problem solving could be: emergent problems are 'optimally' solved (i.e. derived) by a decentralized system (i.e. micro-dynamics' simulation).

el, it belongs to the design language. Then L_2 to L_1 causal power is impossible.

Up to here we might have mixed design/observation with micro/macro as it is often the same: we conceive agents and we are very happy to show their collective behaviour to colleagues. However, it can be interesting to distinguish the micro/macro from design/observation.

Sawyer's definition is based on the existence of a macro-entity external to micro-agents. This existence might provide causal powers to this entity on agents. Therefore, it allows a macro to micro causation we can consider as downward as scale decreases. However, this is different from O'Connor's view as agents do not constitute the macro-entity.

Existence of micro- as well as macro-entities implies they are part of the L_1 which makes that the definition is based on design only. This makes Sawyer's definition contradictory to the emergence test of Ronald et al. as L_2 vanishes.

2.5 Grammar Emergence

2.5.1 Concept

This last definition of emergence is specific as its scope is limited to systems expressed in a particular grammar model. This model provides intuitive definitions for micro/macro and design/observation levels.

Kubik [22] has proposed an approach based on 'the whole is more than the sum of its parts' as inspiration and isometric array grammars [23] as a modelling tool.

The key idea is to define a 'whole' language and a 'sum of the parts' language.

From an initial array configuration, a language is obtained by rewriting using isometric production rules. For a given set of rules P_i, the corresponding language is noted $L(P_i)$.

We can sum up the proposal as follows:

$$\underbrace{L(\bigcup_i P_i)}_{Whole} \underbrace{\supset}_{More} \underbrace{superimposition_i}_{Sum} \underbrace{(L(P_i))}_{Parts}$$

We do not give the definition of the superimposition operator here.

Emergence is the case of an array being in the whole language but not in the sum of parts. The first is obtained by putting all parts together and deriving configurations, the last by deriving configurations for every part separately and putting results together afterward. Putting together is the way we get a macro-entity from micro ones, and derivation is the way to get the language (L_2) we observe from the rules (L_1) we designed.

2.5.2 Discussion

When someone hears 'the whole is more than the sum of its parts', he or she might reply very fast that a system is composed of its parts and therefore cannot be more.

To go beyond this triviality, Kubik's elegant idea is to switch micro/macro with design/observation. This makes things comparable as Kubik defines his gap between two sets of arrays (similar to L_2 and an L'_2) at the observation level. Unfortunately, the definition is not so homogeneous as putting together is different for arrays and for rules. There is another drawback: without restrictions on rules, it might be impossible to determine if an array is emergent.

Kubik's idea is close to an informal definition of emergence of Demazeau [24] stated in the VOWELS framework [25] for multi-agent systems (MAS). This framework suggests a description of such systems as agents (A) in their environment (E), using interactions (I) forming an organization (O). Then the pseudo-equation of Demazeau [24]:

$$MAS = A + E + I + O + emergence$$

can be seen as:

$$\underbrace{L(MAS)}_{Whole} \underbrace{\supset}_{More} \underbrace{\sum_{v \in vowels}}_{Sum} \underbrace{(L(v))}_{Parts}$$

with VOWELS as an alternate micro-partition of a macro MAS.

3 General Framework

3.1 The Minimal Setting

We chose to survey very different works. However, the following setting is shared by most of emergence definitions:

(1) something appears, it is a candidate to the title of emergent

(2) it happens within the dynamics of a system

(3) at least 2 levels/languages are distinguished

(4) it satisfies a criterion that makes it an emergent

The first two points describe a system where something pops up, usually called a phenomenon.

The last point describes a criterion that defines the emergent subset of the larger set of things that pop up (we said the phenomena); this criterion uses the notion of levels (third point).

3.2 Open Issues

Any precise definition requires refinements about the minimal setting. Most of the time, the refinements concern the definition of levels and what kind of criterion we define between them. We come back to these two points but first we want to clarify a prerequisite: the observation of the phenomenon.

3.2.1 Observation

The possibility to perceive the emergent phenomenon is not clear. Actually, we have to consider two issues, perceive the phenomenon and perceive its 'emergenceness'. We focus here on the phenomenon itself as its 'emergenceness' depends on the chosen criterion.

If we consider a phenomenon P, we may wonder what ways we have to observe it. Bonabeau and Dessalles suppose we have a detector. For Ronald et al. the emergent phenomenon is the word of the L_2 language. Sawyer describes agent internalization which seems to be a way for the agent to perceive the phenomenon. Finally, Kubik's phenomena are words.

We may wonder what happens to computability. For example, can we consider that a phenomenon is a computable property of the system's trace? Furthermore, we might wonder if the Church-Turing thesis makes the space of 'any device which gives a binary response to its input' (see 2.1.1) equivalent to the space of Turing machines.

Unfortunately, observation is not always clearly defined. This is important if we consider that emergents are a subset of observable phenomena.

3.2.2 Levels and Downward Causation

One of the main issues about emergence is to clarify what the different levels in the system are. We identified two principal conceptions:

- design/observation distinction [13] (close to internal and external descriptions of Demazeau and Müller [16])
- micro/macro or local/global levels possibly structured into a hierarchy [7, 21]

In table 2, we summarize how these two distinctions are expressed in the presented works.

One might ask: 'Do we always design micro and observe macro?'. The definition from Bonabeau and Dessalles does not deal with design. Sawyer claims a macro-entity must exist but it is not clear if it must be artificial (and then designed). Kubik makes the distinction between the two relations but still the whole system is designed micro (as the union of rules) and observed macro.

Table 2. Levels definitions

Author(s)	Micro/macro	Design/observation
Bonabeau et al. [7]	hierarchy	observation only
Ronald et al. [13]	L_1/L_2	L_1/L_2 ($L_1 \cap L_2 = \emptyset$)
Darley [17]	agents/phenomenon	agents/phenomenon
Bedau [18]	micro-dynamics/macro-state	micro-dynamics/macro-state
Kubik [22]	parts/whole	rules/configurations
Sawyer [21]	agents/emergent	design only

Then we have a macro-phenomenon. Based on where observation takes place, Müller [26] distinguished:

Strong emergence: 'When the observer of the phenomenon is inside the system, endowing the phenomenon has causal powers.' This is very close to Sawyer's emergence and certainly related to the idea of internal description, as the observation mechanism must be inside the system's entities.

Weak emergence: 'When he (the observer) is not inside the system, making the phenomenon an epiphenomenon', which corresponds to the L_2 language of Ronald et al. [13] excluding all the design and also to Forrest's definition of emergent computing [27].

Internal observation allows causal powers and we are back to the question of causation. Many philosophical works about emergence have stated 'downward' causation has a key feature [20, 28]. The impossibility of such a feature is sometimes used to exclude emergence from the ken of artificial systems.

We have seen the definition of Sawyer's downward causation from a macro-entity to micro ones. All these entities are part of the design language. Müller [26] suggested that this macro-entity where macro-phenomena leave their prints might be called the environment. This provides a multi-agent formulation where agents with reduced action/perception (micro) fields interact with a shared environment (macro).

However, this definition is weaker than O'Connor's who required the macro-entity to be composed of the micro ones to assess downward causation. In this case we have one single system which can be seen as composed or as a whole. This small modification makes the levels completely different; it results in a radically different notion of emergence. Indeed 'downward' causation depends a lot on what we mean by 'up' level, 'down' level and then 'downward'.

3.3 Criterion

We have generated some phenomena in a multilevel framework. Some of them are called emergent, according to a defining criterion. We have jointly discussed bidirectional causation and levels because of a direct dependence.

Bonabeau and Dessalles define emergence as a sudden concision of the system's description given by a detection apparatus. Their criterion is explicitly based on a complexity measure and emergence is an irregularity in the evolution of this complexity during the system's activity. The criterion of Ronald et al. is a surprise. We think we can reformulate this as 'how complex it is to describe what we see with respect to some information', i.e. design information. This is interesting because Bonabeau and Dessalles describe emergence as a shift of such a complexity. Both definitions make emergence close to the notion of relative (to some information) descriptive complexity.

Table 3. Some properties of the criteria

Author(s)	Criterion	Binary/gradual	Complexity
Bonabeau et al. [7]	complexity shift	binary	explicit
Ronald et al. [13]	surprise	gradual	implicit
Darley [17]	$u(n)/s(n)$ balance	gradual	implicit
Bedau [18]	simulation optimality	binary	implicit
Kubik [22]	set difference	binary	no
Sawyer [21]	downward causation	binary	no

For Bedau [18], two criteria for emergent phenomena are:

- 'Emergent phenomena are dependent on underlying processes.'
- 'Emergent phenomena are autonomous from underlying processes.'

This autonomy seems difficult to define, especially for artificial systems, because the system runs as designed and its design is available. Autonomy for Bedau is the need for simulation, as simulation is the only way to predict. The terms 'algorithmic effort' [18] or 'amount of computation' [17] suggest that optimality is relative to some kind of time complexity. Therefore, they make emergence close to relative (to simulation) time complexity.

Kubik gives an alternative to such complexity considerations with a criterion based on a gap between languages. Although his definition of a whole system that is more than the sum of its parts can be considered as a difference of generative power between systems, for a specific phenomenon (array), emergence is a binary criterion.

Finally, Sawyer's definition is based on the presence or absence of downward causation that is hardly a complexity issue or a gradual criterion.

Table 3 summarizes some properties of the criteria we have seen.

One problem is to know how far we can decide whether a given phenomenon is emergent or not (satisfies the criterion). For an observed phenomenon, can we decide on its emergenceness?

Bonabeau and Dessalles: The criterion is decidable as far as we have access to the complexity measures before and after a detector's activation.

Ronald et al.: No decidability assumption is made about surprise.

Bedau and Darley: Optimality of simulation might be impossible to decide; usually, empirical support exists.

Kubik: No assumption made on the decidability for the two languages.

Sawyer: Causation of a macro-phenomenon on micro-entities might be decidable if the micro/macro is well defined and causation is given a decidable definition.

4 Conclusion and Perspectives

With this survey, our goal was to identify a 'computer science' emergence definition (the reader interested in a more philosophical approach might consult Ali et al. [29], Stephan [30] and Kim [31]). We have isolated a minimal setting, small as definitions are significantly different. These differences might fit more or less your intuition of emergence.

By going through these definitions, we have noticed that emphasis is usually put on the criterion proposed. However, for a computational definition, we think the following points should be refined:

- How do we apply levels to existing systems?
- Can we tag a phenomenon as emergent in a computable way?

We might also explore to what extent a specific definition of emergence is linked with definitions of self-organization or complexity and other terms we usually meet in the field of complex systems.

Nonetheless, the reason why we wanted a computer definition is the 'much from little' idea that Holland associated with emergence [32]. Then a lazy computer engineer would certainly be emergentist to work little for a great result. Moreover, if little is all we can do, emergence could be a way to go beyond our limits. Thus emergent engineering sounds like an appealing research track.

This idea is already present in Ronald et al. [13] and Müller [26]. We can also refer to the 'New Emergent World models Through Individual, Evolutionary and Social learning' (NEW TIES) project, the idea of 'emergent intelligence' [33] or the ADELFE methodology [34].

In the future, we hope to progress in this direction by using insights provided by definitions and mechanisms suggested by widely accepted emergence examples (social animals, markets), and Holland's inspiration as a goal.

5 Acknowledgement

We thank the French Government (DGA) for supporting the research reported in this paper.

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