Advances in Complex Systems

HOW DYNAMIC AGGREGATES MAY ACHIEVE EFFECTIVE INTEGRATION

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Requirements for warranted identification of 'emergence' of new entities in nonlinear chemical dynamic systems are considered in terms of developments in both chemistry and in philosophy. In particular, a recently reported example of emergence of coherence in a set of electrochemical oscillators is examined. The philosophical theory of 'response dependence', proposed as a 'third way' in the realist-antirealist controversy, and a contemporary discussion of the concept of substance are also employed. The conclusion is reached that when a set of chemical reactions achieves such closure as to generate a limit cycle or strange attractor, properties of a test entity are altered. To the extent that this can be shown to be the case, it is appropriate to consider that a novel (emergent) entity has come into existence. Existence of the limit cycle brings about major changes in the levels (concentrations) of reactants that generate that cycle. Emergent entities of the type discussed in this paper are not adequately dealt with by the standard philosophical theory of wholes and part ('mereology'). That theory should be extended or modified.

Keywords: emergence; chemical dynamic systems; mereology; substance; response dependence; ontology; ontological emergence.

1. Emergence

The word 'emergence' was first used [1] in English during the sixteenth century — as a fancy and learned way to refer to the process of coming up out of the sea. Over the intervening centuries the word has acquired a number of other meanings — all metaphorical. Two recent books titled *Emergence* mainly deal with computational algorithms, although they also cover a variety of other topics. Holland [11] has a

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catchy, but vague, characterization of emergence: ‘much comes from little.’ Johnson [14] is a little more specific: 'the movement from low-level rules to higher-level sophistication is what we call emergence.' Dictionaries give more formal, and also more varied, definitions [25]:

1) to rise or come forth from, as from water or other liquid.
2) to come forth to view or notice, as from concealment or obscurity.
3) to come up or arise, as a question or difficulty.
4) to come into existence; develop….
5) to rise, as from an inferior condition.

Current philosophical discussions of emergence (e.g., [12], [19]) generally focus on the fourth meaning — 'to come into existence.' But events of at least three distinct kinds can fall under that definition.

1) Properties can emerge — liquid water has a specific *viscosity,* but it makes no sense to talk of viscosity of water molecules. The property of viscosity comes into being when water vapor condenses to produce the liquid.
2) *Individuals* can emerge — as when new protein molecules are synthesized from a soup of amino acids and other constituents.
3) *Kinds* of entities can emerge — as when *homo sapiens* developed from *australopithicus*.

Elsewhere [3] I discuss emergence of properties, this paper is concerned with the origin of individuals.
When can one *properly assert* that novel entities (new things) have emerged? (This is what philosophers call 'ontological emergence.') Although current philosophical discussions of emergence emphasize entangled quantum systems, some explicitly note [19, 22] that nonlinear dynamics of macroscopic systems also might generate emergent behavior — quite independent of quantum-mechanical details. Subsequent sections of this paper will focus on what criteria might be appropriate to decide whether emergence of that latter sort in occurs in specific chemical dynamic systems.

2. What 'Is' Might Mean

Recall the widely quoted observation of William Jefferson Clinton [16]:

> It depends on what the meaning of the word 'is' is.

The verb 'to be' functions in a large number of distinct ways in Indo-European languages. The way the many forms of verb to be are used in the most ancient Indo-European sources (Greek epic poetry ascribed to Homer and Sanskrit sacred books *The Vedas*) indicates that *persistence* (e.g., being alive) was the original characteristic meaning of 'being' [15]. This suggests that some kind of stability over time might well be taken as the basic, and central, aspect of being. Consistent with this view, *Aristotle* (384-322, B.C.) held that the fundamental existing things are persistent beings (*ousia,* generally translated into English as 'substances'). He held that each such entity can usefully be considered to be composed (in some sense) of two components: *hyle* (rendered as 'matter'), and *morphos* (construed as 'form'). This *hylomorphic* theory, along with other Aristotelian ideas, fell out of favor during the rise of modern science.

Strongly influenced by Newtonian physics, David Hume (1711-1776) claimed [10] that reality consists of disconnected temporal slices — *'events.'* In the first half of the twentieth century, Alfred North Whitehead (1861-1947), rejected both those doctrines and held that what is fundamental is *process* — coming to be and perishing [27]. Clearly, deciding whether or not ontological emergence occurs in any particular case of dynamic chemical interaction must involve some specific idea of the meaning of the word 'is', and would probably imply adopting some ontological category — whether it be substance, event, process, or some other — as fundamental.

In a contemporary discussion of the meaning of the concept of 'substance,' Ruth Garrett Millikan [21] holds:

> Substances…. are whatever one can learn from given only one or a few encounters, various skills or information that will apply to other encounters. ….. Further, this possibility must be grounded in some kind of natural necessity. …..The function of a substance concept is to make possible this sort of learning and use of knowledge for a specific substance.

According to this author, physical individuals, historical individuals, stuffs, natural kinds, symphonies, familiar stories, and many other sorts of things, all merit the designation 'substance.' Substances (for Millikan) provide — in a small number of interactions, and in virtue of 'natural necessity' — information that will also pertain to subsequent encounters. According to Millikan, each substance involves an 'ontological ground of induction' (sometimes called an *essence*).

3. Response Dependence

Considering fundamental ontological categories draws us close to a major question much discussed by philosophers in recent years. Is 'truth' *detected,* or *projected*? 'Realists' hold that how-the-world-is does not depend on any observer: 'anti-realists' assert that what is known depends so much on activity of the knower that it makes little sense to talk of observer-independent reality. Recently a 'third way' has been proposed [23] to help resolve this controversy. The central idea of this approach — called 'response-dependence'— is tersely summarized [13] in the formula:

… x is C if in conditions K, Ss are disposed to produce x-directed response R.

That is, some property (x) is properly considered 'response-dependent' (C) if, under certain specified or specifiable conditions (K), particular subjects (S) produce (invariably, or for the most part) a determinate response (R) to that property. This amounts to emphasis on results of interaction, without restriction as to what sort of transaction might be involved. The response-dependence approach is said to avoid 'recourse to unobservables' (of which realists are often accused) and also to shun over-dependence on action of human observers (that often seems characteristic of anti-realists). Proponents claim that the response dependence theoretical approach is especially useful in dealing with value judgments, both moral and artistic.

4. Emergence in Chemical Dynamics

When chemical individuals (species, molecules, concentrations, activities, ….) interact in open, high affinity, situations, it often happens that temporal and/or spatial coherence may result. Under some conditions, closure of networks of chemical processes [5] gives rise to regions (in space and time) displaying new and more or less stable properties. These aggregations are called usually called 'dissipative structures' [18]. This designation emphasizes two important features of such coherences — as structures, they have the ability to return to an earlier configuration after disturbance, but as dissipative they degrade free energy (generate entropy) in the normal course of their existence.

Consider a flow-system minimal bromide oscillator [6, 8]. In the high-flow steady state (and the unstable steady state), bromide concentration is low. If parameters change, and the system moves to a limit cycle, bromide concentration oscillates about an average bromide concentration that is *much higher* than the original bromide concentration. Any bromide detector applied to this system will register an average concentration much increased *by the limit cycle*.

Whenever any collection of agents achieves persistent integration, then that collection, as a unit, can become part of larger aggregates. Computer games provide particularly clear examples. Structures called 'gliders' in the digital game 'Life' can be used as components of general purpose computers [11].

Chemical dissipative structures have several distinguishing characteristics:

- They are necessarily and continuously connected to their environment by material and energy flows.

- They replicate a specific sequence of states indefinitely – in this sense, they ‘persist’ through time.
- Dissipative structures tolerate significant variations in conditions — and also modify pre-existing entities, fluxes, and flows by their functioning.

Each dissipative structure must satisfy several constraints [2].

- The system must be far from equilibrium (have high 'affinity' in de Donder's sense) [18].
- Direct or indirect autocatalysis must operate.
- Mechanisms that reduce autocatalyst activity must exist.
- System parameters must be such that a limit cycle (or strange attractor) exists.

If the ‘response dependence’ outlook is adopted, then open-system limit-cycle chemical oscillations fulfill all of Milllikan's criteria for meriting the designation 'substance' — identity (more or less) over time, and also through interactions, and basis in ‘natural necessity.’ Systems exhibiting limit cycle oscillations interact with other systems while maintaining oscillatory behavior — they clearly are persistent in that dynamic sense and also interact with the environment. Due to the persistent oscillations, average concentrations are different than no-cycle concentrations, therefore effects on interacting systems will differ because the cycle exists, necessarily giving rise to some change (a response) in some or all interacting systems. That response persists while the oscillation continues. The source of the response is the closure of the network or relationships that defines the structure — this clearly is the 'basis in natural necessity' required by the third of Millikan's criteria for ‘substance’ status.

5. On Detecting Emergence

Millikan’s prime interest is ‘philosophy of mind’. ‘Response-dependence’ theorists are mainly interested in moral and esthetic choices. It is not surprising that all these authors think in mainly anthropomorphic terms — focusing their discussion on such concepts as such as 'knowledge' and ‘truth.’ But one need not be so human-centered. Inanimate agents also undergo interactions, and are modified by them. That is to say, even inanimate objects ‘learn’ in a broad sense. Variations in the oscillations of calcium ion concentrations in the animal brain have consequences for the levels of many inanimate chemicals. These levels, in turn, influence behavior of that organism, quite apart from any consciousness that may exist.

In *The Sophist (246-247)* — a late work [8] — Plato (427—347 B.C.) discussed a 'sort of war of giants and gods' then going on, between 'those who make being to consist in ideas.....they are civil people enough' and those 'who define being and body as one..... and terrible fellows they are.' He proposes an approach different from that of either of the two factions mentioned.

> My suggestion would be that anything that possesses any sort of power to affect another, or to be affected by another even for a moment, however trifling the cause and however slight the effect, has real existence; and I hold that the definition of being is simply power.

This ancient notion is the basis for the criterion of existence generally used by chemists.
If the criterion for existence of a novel entity is interaction, then it seems reasonable to assert that any entity may serve to detect the presence of an emergent. The test of ontic emergence in chemical systems is (or ought to be) whether some (any) entity is differentially influenced by the closure of relationships that defines a dissipative structure. From this point of view, 'to be' (at least for chemical dynamic systems) is to persist long enough, through sufficiently significant interaction with surroundings, that an effect on some (any) test entity results.

6. A Specific Example

Kiss, Zhai and Hudson, [13] have recently studied an electrochemical cell with sixty-four nickel rod electrodes (an 8x8 array) in sulfuric acid. **(Figure 1)**.

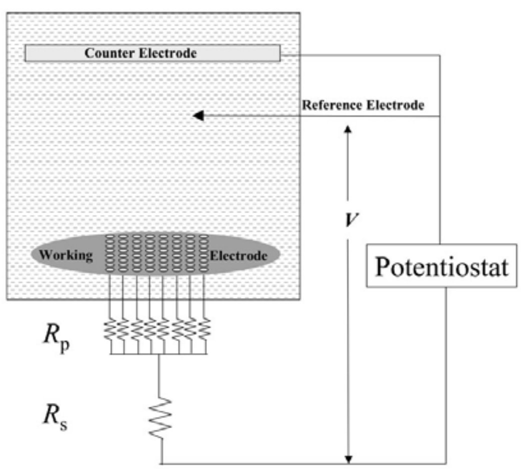

Figure 1. Experimental setup for experiment illustrating emergence of coherence of electrochemical oscillators [17].

When the (parallel) resistance associated with each of the electrodes (R_p) is small and the common (series) resistance (R_s) is correspondingly large, the nickel electrodes act independently, and generate limit-cycle oscillations that have a common frequency but a range of phases. The phases of the oscillations are evenly distributed about a single closed curve. **(Figures 2A, 2B.)**

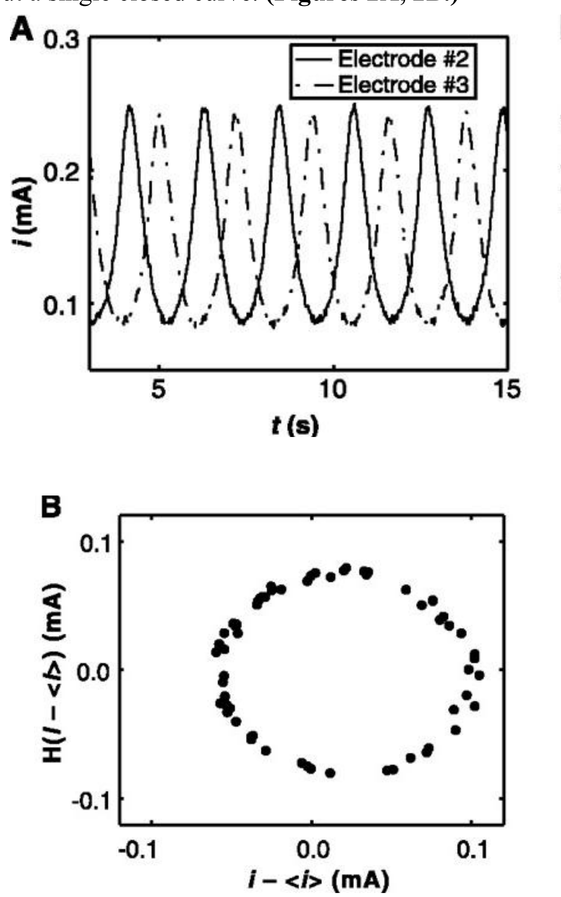

Figure 2. Experimental results with weak coupling between electrodes. A) current – time traces for two electrodes showing limit-cycle oscillations. B) variation of phases of oscillation of electrodes, defining a single closed curve. [17].

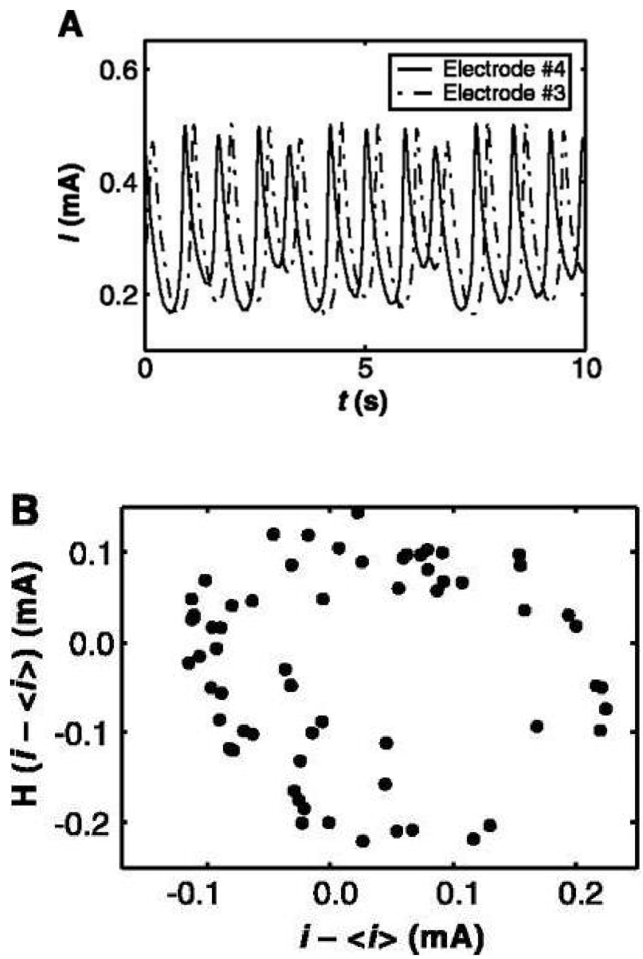

Figure 3. A) Current-time curves showing irregular oscillations. B) Distribution of phases of irregular oscillations, showing results suggesting a strange attractor [16].

For the same setup under other conditions, chaotic oscillations result, and the phases of the oscillators suggest existence of a strange attractor rather than a limit cycle**. (Figures 3A, 3B.)**

As R_s /R_p ratio decreases, interaction between oscillators (K) increases. Once the interaction increases beyond a critical value, the fraction of entrained oscillators sharply rises **(Figure 4B).**

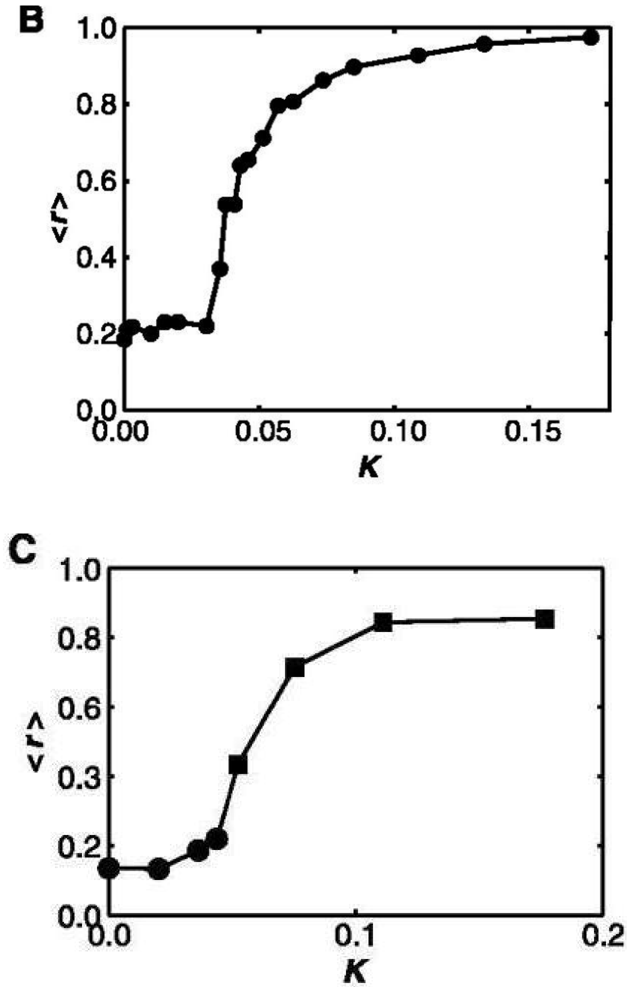

Figure 4. Effect of increase of coupling of electrodes on fraction of coherence of oscillations [17]. B) regular (limit cycle) oscillations, C) irregular (chaotic) oscillations.

As interaction between chaotic oscillators increases beyond a critical value, entrainment also occurs, but not so sharply as in the previous case**. (Figure 4C.)**

The transition from random phase of oscillations to coherence can engender a response in the rest of the world. It would be an easy matter to use the sharp increase in coherence of these electrochemical oscillators as a switch to control some external event. To the extent that this is the case, the collection of oscillators, as a unit, may appropriately be considered a new (emergent) entity — a substance in Millikan's sense of that term.

7. Toward a New Mereology

'Mereology' is a name 'used generally for any formal theory of part-whole and associated concepts' [23] Classic mereology was developed by Stanislaw Leśniewski (1886-1939) partly in order to resolve 'Russell's paradox'. (e.g., If a Cretan says 'All Cretans are liars', should anyone believe him? [24]) A 'merological whole' is an individual that is composed of parts that are themselves individuals. Any number of individuals of any sort whatsoever (the star Sirius and your left shoe, for instance) can comprise a mereological whole. Both classical mereology and also more recent versions [7, 20] make the assumption that parts are not changed by being associated into wholes.

Simple versions of kinetic theory assume that gas molecules occupy *no* volume and have *no* attractive or repulsive forces between them, and on this basis derive the ideal gas law, $PV = nRT$. Such assumptions are useful, even though they are generally unrealistic, because they provide a reference prediction — what would be expected if, *per impossible*, those assumptions were to hold. The kinds and extent of observed deviations from the predictions of the ideal gas law in any particular experimental situation indicate the kinds of extensions and modifications that need to be made to the simple theory, adequately to deal with that case.

Standard philosophical mereology may be regarded as the simple 'no interaction' theory, analogous to the primitive version of kinetic theory. Just as complications need to be added to basic kinetic theory to deal with real gases, so the mereology of Leśniewski needs to be adjusted to deal with chemical combinations.

In chemical dissipative structures, existence of a limit cycle *changes* the average concentrations of components of the system. The dissipative structure is a whole, with component concentrations as parts. Parts are modified by their composition into a whole. This situation is excluded, by definition, from standard mereology. Mereology needs to be extended [4], to apply to cases where the assumption that wholes do not influence parts does not apply.

8. Conclusion

Whenever a number of agents (e.g., chemical species) interact in such a way (and under such conditions) that a limit-cycle oscillation (or approximation thereto) develops, then the net effect of that aggregate of agents on some interacting (test) entities is changed, with the result that the activity of those test entities is modified by the existence of the limit cycle. On this basis, identification of the collection of agents as a new (emergent) entity is warranted.

To put this conclusion in language* of formal logic [19], let us suppose we have a set of several agents ($x_1, x_2, x_3, \ldots x_i$ — let's call them '*X*, the set of *x*s' or simply the *x*s. In the cases of interest here, each *x* is a concentration (activity) of some chemical species (an entity distributed in space). Each *x* may interact with other *x*s, and with itself (e.g., exponential decay, and autocatalysis). Also, consider an appropriate test agent *y* which has some property *F* when the *x*s do not interact in a significant way. If the *x*s do interact so as to generate a dissipative structure (e.g., a limit cycle oscillation, or reasonable facsimile thereof, that persists for a more or less extended period of time) – indicated *X I*, then y may have different (other than *F*) properties (~*F*) due to interaction between *y* and *X*, the set of *x*s. If the latter condition prevails, then the interaction of the *x*s has brought about a response in the test agent y (*F* becomes ~*F*). On a response-dependence basis, this is good warrant for asserting that an emergent entity *z* exists, and that the *x*s are parts of *z* – indicated *X P z*.

This conclusion can be written out in symbols. If *P* is the part relation, *I* indicates that the set of *x*s do interact to yield a limit cycle (or near equivalent), *F* is a test property, and *y* is an agent that, in the absence of significant interaction among the *x*s, has property *F* – indicated $\exists y(F(y))$ – then:

$$(\exists x_1 \ldots \exists x_i) \in X \,.\, \left[\left\{\sim\ X\ I \supset \left(\exists\, y \left(F\left(y\right)\right)\right)\right\}\right]$$

$$(\exists x_1 \ldots \exists x_i) \in X \,.\, \left[\left\{X\ I \,.\left(\exists\, y\left(\sim\ F\left(y\right)\right)\right)\right\} \supset\ \exists\, z\left(XPz\right)\right]$$

The symbol *z* refers to an emergent entity of which the *x*s are parts. In other words, it is legitimate to speak of the emergence of a new entity *z*, iff (if and only if) certain agents (the *x*s in this case) interact in such a way that some (any) test entity (*y*) suffers a change in its properties (*F* becomes ~*F*) due to the closure of that interaction (*XI*). If such closure [5] does occur, then the *x*s are correctly considered as parts of the emergent entity *z* — that is, *XPz*. This requirement is the criterion of emergence that has been sought in this paper.

It should be mentioned that any such *z* might interact with other agents, of similar or different sorts, to generate yet larger emergent entities, say, one of the *w*s. Also, each and every one of the *x*s, is itself an emergent entity made up of components,

* Symbols have usual [24] meanings: a period (.) denotes addition ('and'), ~ means negation ('not'), ∨ is inclusive 'or' (Latin *vel*), ∃ is the existential quantifier ('there is a(n) ..'), ∈ denotes class (set) membership, and ⊃ indicates implication ('if...then').

perhaps the *u*s. But then every one of these integrations can fail to persist, with consequences both for its constituents and for whatever things of which it may be a component.

The main point of the previous paragraph was stated much more elegantly by Alfred North Whitehead:

> The general aspect of nature is evolutionary expansiveness. … 'Value' is the word that I use for the intrinsic reality of an event. ….The problem of evolution is the development of enduring harmonies of enduring shapes of value, which merge into higher attainments of things beyond themselves. …. The endurance of an entity represents the attainment of limited aesthetic success, though if we look beyond it to external effects, it may represent an aesthetic failure. Even within itself, it may represent the conflict between a lower success and a higher failure. The conflict is the presage of disruption.[27]

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