Chapter xxx

Emergence, Entities, Entropy, and Binding Forces

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1. Introduction

Emergence is a central, although loosely defined, concept within the complexity community. One often hears that a property is not emergent unless one is surprised by its appearance. This is a naïve form of what is called *epistemological emergence*, see [O'Connor 2003]. But whether or not one is surprised that something has a property is really not relevant to much other than one's psychological state or intellectual powers. The surprise of an observer has nothing to do with a property or whether something displays that property.

In a recent paper [Bedau 2002] defined what he called *weak emergence*, which is intended to correspond to the generally accepted notion of emergence in the complexity community. For Bedau, a phenomenon is weakly emergent if it arises in the course of a simulation (or in reality) but is not anticipated in advance. Bedau's primary example is the glider in the Game of Life [Gardner, 1970, 1971].

This paper will explore a characterization of emergence from a different perspective. We will identify emergence (in at least some of its forms) with entities. In many if not most cases, *emergence* refers to the emergence of something, i.e., an entity.

We also offer a classification of entities, of which two are of most interest:
(a) physical entities, for which one can describe both a physical mechanism for their existence as entities and a metric for the degree to which they qualify as emergent and (b) structural/process entities (the kinds that tend to be most interesting), which include biological and social entities. In both cases (and perhaps most fundamental), the mechanisms that lead to the formation and persistence of these entities expel entropy from the entity. In the first case, the mechanisms that expel entropy run in some sense for free, illustrating that emergence is a fundamental fact of life. In the second case, the mechanisms that expel entropy require the importation of energy, resulting in entities that are now famously called "far from equilibrium."

1.1. Background

According to Bedau, emergence is characterized by the following two hallmarks.

- Emergent properties are dependent on underlying processes.
- Emergent properties are autonomous from underlying processes.

Perhaps more to the point, emergence is typically considered a relationship between macro and micro phenomena—one in which a macro phenomenon in some sense *emerges* from underlying micro phenomena. Bedau defines three increasingly restrictive categories of emergent properties.

- **Nominally emergent:** macro level properties that do not apply at the micro level but that can be reduced to them. Bedau's example here is a circle, which he says consists of a collection of points, each of which individually has no shape. So being a circle is a property of the "whole" but not its "parts." But, he continues, if you know that all the points in a collection of points are equidistant from a given point, then you can derive the fact that the collection is a circle.

  Perhaps a more complex example (but not Bedau's) is that of a (macro-level) house that has the property of having two bedrooms. The predicate "number-of-bedrooms" does not apply to the (micro-level) components of a house such as paint, lumber, sinks, nails, roofing, and drywall. But with enough definitional work, perhaps number-of-bedrooms could be defined in terms of these components. This is emergence as little (if anything) more than entailment. See our discussion below of designed (the house) and symbolic (the circle) entities.
- **Weakly emergent:** macro level properties that could not be predicted from the micro level except by simulation. Bedau uses gliders in the Game of Life as his prototypical example.

  All weakly emergent properties are nominally emergent, but they are derived in so complex a way that the work required to derive them is at least as complex as the work required to allow them to emerge. Although we do not have time to explore this issue here, Bedau's weak emergence is in some sense equivalent (although Bedau doesn't make this claim) to recursive enumerability, i.e., a property that must be computed to be observed.
- **Strongly emergent:** macro level properties that *cannot* be explained by any combination of explanations from the micro level. It is unlikely that there are any such properties—strong emergence is inconsistent with any modern scientific conception of the universe—but if there were, consciousness would be a current candidate. Strong emergence is emergence, which, by definition, is spooky and mysterious.

2. Defining Entities

When speaking of phenomena or properties that are meaningful at a macro level, one is inevitably forced to speak of entities that either participate in those phenomena or that have those properties. Although there may be some situations in which macro phenomena or properties make sense without speaking of entities, our fundamental frame of reference seems to be in terms of entities.

In this paper we will simply understand the issue of macro vs. micro to be one of macro entities vs. their micro components. Our task will be to distinguish between (a) macro entities that are composed of micro components and (b) simple aggregations of micro entities that don't deserve to be called entities.

We will say that a property of an aggregation is emergent if its definition depends on the means (i.e., the mechanisms, design, structures, forces, or constraints), if any, that bind the aggregation's components together. Thus, if a property of an aggregation depends only on the components of the aggregation, that property is not emergent. To be emergent, the property must also depend on whatever it is, if anything, that binds the aggregation together. If there are no such binding forces, the aggregation cannot, by definition, have emergent properties.

Here are some examples of aggregate properties that are and are not emergent.

- The mass of a bag of marbles is not emergent because mass does not depend on the fact that the marbles are in the bag.
- The possible use of a bag of marbles as a club is emergent because that use does depend on the fact that the marbles are in the bag. (See below for our discussion of symbolic entities.) Bedau's circle is also emergent as a symbolic entity.
- The miles-per-gallon rating of an automobile is emergent. The property of miles-per-gallon does not mean anything with respect to the component of an automobile simply as a collection of parts. It has meaning only with respect to the components when bound together as an automobile.

This definition of emergent is consistent with Bedau's notion of nominal emergence—which, recall, includes weak emergence. The distinction we are making is that a property is emergent if it's nominal derivation depends not only on the component elements but also on how those component elements are bound together.

This seems quite straightforward and reasonable, almost obvious. But the focus on how elements are bound together has profound implications. One implication is that any property that does not apply directly to fundamental particles is emergent because any such property necessarily depends on how the elements to which it does apply are constructed. This definition of *emergence* thereby alerts us to pay special attention to the means that bind aggregations together since it is the binding mechanisms that lead to emergence.

Given this definition of emergent properties, we can define an entity simply as follows.

An aggregation is an entity if it has one or more emergent properties.

Applying this definition to the preceding examples:

A bag of marbles is an entity (but only a symbolic entity) because of its possible use as a club.

- An automobile is an entity because it has the emergent property miles-per-gallon.

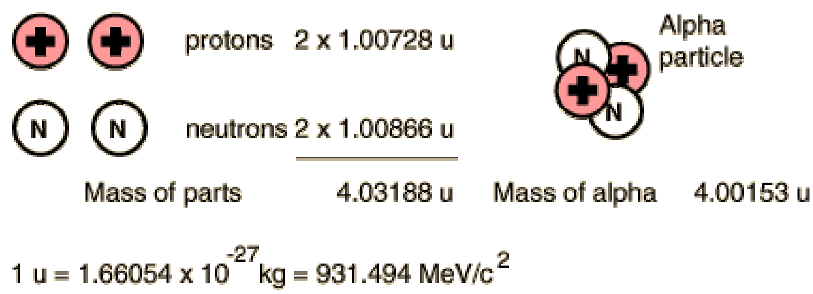
3. Categories of Entities

It is useful to group entities into categories. The following table summarizes our categorization. It is explained in the sections to follow.

Requires energy to be sustained?	Intrinsically bound entities	Extrinsically bound entities
No. At equilibrium.	*mass-based entities*	*attractor-based entities*
	e.g., an atomic nucleus	e.g., a lake
Yes. "Far from equilibrium."	*process/structure entities*	*designed entities*
	e.g., a living cell, a nation-state	e.g., an automobile, woven cloth

3.1 Mass-based entities

A mass-based entity is an entity whose mass is less than the mass of its components. The clearest example is that of an atomic nucleus. The mass of any atomic nucleus that has more than one nucleon is always strictly less than the sum of the masses of the protons and neutrons that compose it. A Helium nucleus (an alpha particle), for example, has mass 4.00153u, whereas when considered separately its components have total mass of 4.03188u.[1]



This mass differential exists because less binding energy is needed to hold an alpha particle together than is needed in total to hold the quarks in the four nucleons together when they are independent of each other. (It is that difference that yields the release of energy in a nuclear reaction, either fission or fusion.)

Similar effects occur with other primitive forces.

- Atoms are less massive than their components (nuclei and electrons) considered separately.
- Molecules are less massive than the atoms of which they are composed.
- Gravitational systems (such as the solar system or a galaxy) are less massive than the components of which they are composed.

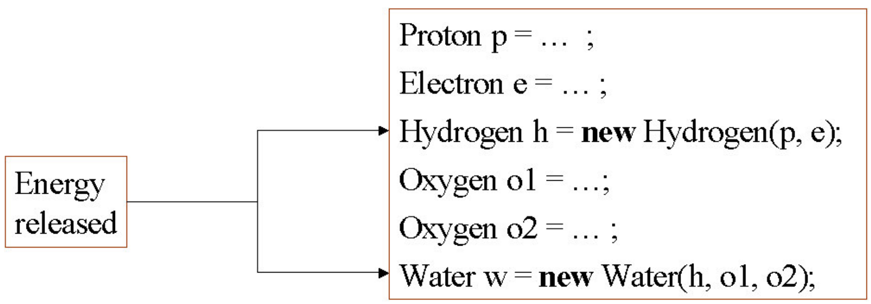
[1] Diagram and figures from http://hyperphysics.phy-astr.gsu.edu/hbase/nucene/nucbin.html.

Although the preceding may sound strange, they are trivially true. Since energy is required to break these entities into their components, and since (at least some of) the energy applied when doing so is retained by the components after the break-up, by the equivalence of mass and energy and the conservation of mass/energy, the total mass of the components after the break-up must be equal to the mass of the original entity prior to the break up plus the retained applied energy. So the sum of the masses of the components must exceed the mass of the original entity. Thus even a handful of wet sand has less mass than the sum of the masses of the sand and the water used to wet it.

This perspective even yields an entity metric. One can define the degree to which an aggregation is an entity as the amount of energy required to separate it into its components. Entityness thus becomes a property with a naively intuitive continuous measure—not a Boolean property.

3.1.1. A Programming metaphor

As a computer scientist I find it convenient think in terms that can be expressed in programming language constructs. Consider the following pseudo-program.



The two lines in which energy is released are the lines in which new objects (entities) are created. Another way of putting this is that object constructors (entity constructors or what might be called *emergence operators*) are built into the universe. They have the property that they release energy when invoked. In other words, in some sense they run for free.

3.1.2. Entropy

The Second Law of Thermodynamics tells us that nothing really runs for free. So what happens to entropy when an entity is created?

Constructors of mass-based entities have the property that they expel entropy from the newly created entity. The entropy of a mass-based entity is strictly lower than the entropy of the entity's components when not bound together as an entity. Whatever binds the components together limits the states they may assume and hence lowers the overall entropy. But since entropy cannot decrease overall, the entropy of the new entity's environment must increase.

The significance of this phenomenon is that entity-forming forces have the effect of aggregating component entities into new larger entities while expelling entropy from the resulting entity into the environment. That this occurs universally and at the most fundamental levels of physics seems to me to be quite significant. Without being too mystical about it, this illustrates that emergence, i.e., the emergence of entities, is a natural byproduct of the way the universe works.

3.2. Attractor-based entities

An attractor-based entity is an entity that exists by virtue of the structure of its environment. For example, a lake exists as water that collects in a basin of attraction. It is not the water that defines the lake; it is the attractor, which is part of the environment. Attractor-based entities are similar to mass-based entities except that the entity (the lake) is separate from the forces that define it. The "stuff" collected in a basin of attraction has emergent properties, e.g., the volume of a lake. But the basin itself also has emergent properties, e.g., its capacity. Energy is required to separate the components from the entity, i.e., to remove components from the basin.

In this case as well as the previous, the entropy flow is the same: from the entity to the environment. Of particular interest is that in both the case of mass-based and attractor-based entities, no energy is required for their persistence. These entities are formed and they persist on the basis of primitive forces.

3.3. Designed entities

Designed entities are a structured collection of components that exhibit properties that the components would not exhibit either individually or collectively were they not arranged according to that structure. Typical examples, which are almost always human-manufactured, range from cloth, clothing, furniture, and mechanical, electrical, and electronic appliances to computers and entities that include embedded computers such as automobiles, satellites, semiconductor chip fabrication facilities, etc. The structure of these entities, if not maintained, typically deteriorates—especially though use.

One of my favorite kinds of entities in this category is woven cloth, which consists of thread arranged according to a weave pattern. As an essentially 2-dimensional object, cloth has a property (area) that its components (threads, which are essentially 1-dimensional objects) do not.

Cloth comes into being when a weave structure is (externally) imposed on a collection of thread components. Unlike mass-based entities, cloth has no intrinsic processes to bind itself together. Nor is cloth bound together by a simple attractor—although perhaps one could argue that it is bound together by the many little attractors that create friction. Although stable if untouched, cloth may fray and unravel with use. It requires mending (the application of additional external energy to rebuild and repair its structure) to maintain its structure.

Like virtually all manufactured objects, cloth has a lower entropy than the unstructured threads of which it is composed. But the process of making cloth is a result of the application of energy; it does not arise spontaneously as a result of fundamental physical forces.

A similar analysis applies to most manufactured entities.

3.3. Process/structure entities

Process/structure entities are characterized by the fact that they have an abstract structure that is maintained by one or more internal processes. The internal processes use energy supplied externally, and they operate only as long as such energy resources are available. Most (perhaps all) biological and social entities are process/structure entities, although not all process/structure entities are biological or social. (See the fire example below). The abstract structure that organizes a process/structure entities persists even as the physical material of which the entity is composed cycles through it.

As an example, consider a corporation, which is defined (in this case formally, although a formal definition is not a requirement for process/structure entities) in terms of its articles of incorporation. The people and property that occupy any particular role in the corporation may come and go. It is the formal structure and processes defined by the corporation's charter that persists. (The fact that most articles of incorporation provide a mechanism for their own modification does not change the fact that at any time, it is the structure and processes defined by that charter that characterizes the corporation.)

Most social and biological process/structure organizations are not built in such a formal manner. Yet they are similar in that they generally have a structure that persists even as the physical material of which these entities are composed comes and goes. It is the job of a process/structure entity's internal processes to use the continually recycled physical materials to maintain the entity's abstract structure. Consider, for example, how the physical substance of any biological entity is constantly being renewed.

A process/structure entity's ongoing binding processes are the means that keep it bound together as an entity. These binding processes are analogous to the ongoing processes (the exchange of virtual particles) that bind mass-based entities together. The forces that bind a process/structure entity together are typically quite complex and are not as simple as those that bind mass-based and attractor-based entities together.

Process/structure entities require a source of energy to power their binding processes—and hence to hold themselves together. This contrasts with mass-based and attractor-based entities, whose binding processes run for free. This need for energy is similar to the need that design-based entities have for external energy to hold themselves together. The difference is that design-based entities need energy to allow an external agent to repair their externally imposed structures. Process entities need energy to run the internal processes that bind them together. Since they depend on the continual consumption of energy to hold themselves together, process/structure entities tend to be far-from-equilibrium systems.

The framework within which a process/structure entity's binding processes operate defines the entity's *infrastructure*. The prototypical example is the circulatory system of a biological entity. Like mass-based and attractor-based entities, process/structure entities expel entropy. They differ from mass-based and attractor-based entities in that they import energy to do it.

We will consider two examples of process/structure entities: fire and a nation-state.

3.3.1. Fire

A simple process/structure entity is (the intuitive notion of) a fire. A fire's primary binding processes are its convection currents and infrared radiation, both of which carry heat throughout the area that defines the fire. The convection flows and the radiation vectors also define the fire's (changing) infrastructure. A fire can exist only when such an infrastructure can be built, which depends upon the physical facts that

- heat can be carried by both gas flows and radiation,
- gases can form convection currents,
- radiation passes through some materials and empty space more easily than through other materials,

A fire persists only as long as fuel sufficient to maintain its infrastructure is available.

3.3.2. A nation-state

A nation-state has a process infrastructure that provides the means by which it operates as a state and an economy. It includes the traditional political and economic infrastructure elements:

- Political infrastructure: elective, legislative, judicial, regulatory, police processes, etc.
- Economic infrastructure: transportation and communication systems (processes), etc.

The multiple ongoing internal processes that define these infrastructures are what bind the nation-state together and allow it to function as a discernable entity. It is the infrastructure that persists over time rather than the elements that play particular roles.

- At least in our government, no one individual fills a political role indefinitely. It is the (infra)structure that remains stable, although it may evolve slowly.
- No one truck, road, or airport defines the transportation system. It is the (infra)structure that remains stable, although it too may evolve slowly.

3.3. We can create new process/structure entities

One nice feature of entity formation is that we can imagine and create new ones. Clearly, any designed object is a human created entity. So are, for example, many of the social systems we have created.

We are also capable of creating the means for creating new entities, which is more interesting. The internet serves as an infrastructure (or something that can be used as an infrastructure) for entities that have come into existence only because it was available as a mechanism to help bind them together.

The authors of the Constitution of the United States recognized and affirmed the importance of infrastructure as binding processes by writing a postal system into the Constitution.

3.4. Other categories of entities

Besides the categories of entities sketched above, there are a number of other categories of entities that don't fit the preceding paradigm. It isn't clear how to describe the binding forces for the following classes of entities. In the following cases, the existence of an entity depends on an additional agent or agency to which the entity gives form.

3.4.1. Temporal entities

Temporal (performances) entities exist in time. They carry and apply energy. Examples include a performance of a musical note/chord/melody, a performance of an algorithm (or a play), virtually any performance. All of these entities exhibit emergence in that there are properties that apply to them that do not apply to their components. A chord, for example, may be dissonant, a property that does not apply to individual notes. A performance of an algorithm (or a play) may achieve a computational (or emotional) result that differs from the results achieved by the performance of the individual components.

3.4.2. Symbolic entities

Symbolic entities require interpretation. Examples include a pair of socks, a sentence, the set of prime numbers, the constitution of a government, the specification of an algorithm, Bedau's circle. These entities also exhibit emergence in that they have properties that their components do not have.

- An algorithm may be proved to compute a result that the individual steps do not compute individually. An algorithm depends on the control structures that bind its components together. Thus the control structures define an organization for an algorithm, but they exert no control over the components other than during its execution. But we are distinguishing the performance of an algorithm, which is a temporal entity, from its specification.
- A sentence has a meaning that is crucially dependent on its syntax, which binds its components together. The situation is similar to that of an algorithm.
- Given how we conceptualized it as a possible weapon, our bag of marbles is a symbolic entity. It was only because we thought of a way to use it as an entity that it had aggregate properties. Other properties might be defined that don't depend on human ingenuity.

3.5. Downward causation

Strict downward causation (macro to micro) is as unlikely as strong emergence. However, downward causation is virtually essential from a practical perspective.

Consider the trajectory of a proton in a molecule in one of the blood cells flowing through my body as I flew across the country to get to this conference. That trajectory is dependent upon my individual mechanical and physiological structure and activities as well as the trajectory of the airplane on which I was riding. That trajectory, in turn, depended upon the weather my flight encountered during the trip, the rotation of the earth, its revolution around the sun, the solar system's revolution around the galaxy, etc. It also depended on decisions made by the pilot and by various flight controllers. These depended in part on regulations put in place by the FAA, a governmental entity, as well as decisions I had made when scheduling my trip, which depended upon the schedule and rates set by Northwest Airlines, an economic entity, which was affected by other regulations promulgated by the FAA, etc. It would be impossible compute any of that without taking into consideration the entities involved as entities.

4. Summary and Conclusions: binding forces drive emergence

A property of an aggregate is emergent if it depends upon whether and how the aggregate is bound together. Entities are aggregates that have emergent properties. Material entities are "free" in that their construction releases energy. The Universe is set up to produce entities and thus to exhibit emergence. Process/structure entities, although also occurring naturally, are not free and exist far from equilibrium. Their persistence requires the continual consumption of energy. We as human beings are capable of imagining and creating both new designed entities and new process/structure entities that have properties we want. We are also capable of creating new infrastructures from which often develop new entities—whose emergent properties sometimes surprise us.

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