EMERGENCE, ENTITIES, ENTROPY, AND BINDING FORCES

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ABSTRACT

The concept of emergence is defined in terms of entities. An entity is an aggregation that has properties that do not apply to its components and whose definition depends on the forces that bind the aggregation together. Four primary categories of entities are identified. Mass-based and attractor-based entities arise naturally and require no energy to persist. Designed entities are typically human-designed artifacts. Process/structure entities are typically social or biological systems that require the continual consumption of energy to perpetuate themselves. In all cases, entities expel entropy into their environment. Two other categories of entities, temporal and symbolic, are explored in less detail. Entities exist as a result of the binding forces that hold them together. The binding forces for mass- and attractor-based entities are fundamental forces and operate, in some sense, for free: emergence is built into nature. The binding forces for designed and structure/process entities require the application of energy and give rise to entities that have come to be known as being *far from equilibrium*. Entities are built on a substrate consisting of component entities and the forces to which those component entities are subject. This parallels the notion of levels of abstraction in computer science. The approach to emergence in this paper relates to the more traditional notions of nominal, weak, and strong emergence. We suggest a relationship between weak emergence and recursive enumerability. We discuss relationships between emergence and scientific reductionism and downward causation.

Keywords: Emergence, entities, entropy, binding forces, persistence, self-perpetuation

INTRODUCTION

Emergence is a central, although loosely defined, concept within the field of complex systems. In a recent paper, Bedau (2002) defined what he called *weak emergence* as a proposed explication for the informal notion of emergence. For Bedau, a phenomenon is weakly emergent if it arises in the course of a simulation (or in reality) but cannot be anticipated in advance.[1] Bedau's primary example is the glider in the Game of Life (Gardner, 1970, 1971). Weak emergence is discussed in more detail in the Background section.

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1 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 the observer is surprised is not relevant to much other than his or her psychological state or intellectual powers. The surprise of an observer has nothing to do with a property or whether something displays that property. Bedau's *weak emergence* does not depend on such a surprise factor. It requires only that the amount of (computational) work needed to show that a phenomenon will emerge is at least as great as the amount of work needed to run a system and see the phenomenon emerge.

This paper explores a characterization of emergence from a different perspective. We identify emergence (in at least some of its forms) with entities. In many, if not most, cases, *emergence* refers to the emergence of something (e.g., an entity such as a glider). But entities are troubling to science. Weinberg, perhaps the ultimate reductionist, puts it this way (Weinberg, 1995):

> "[T]he reductionist view emphasizes that the weather behaves the way it does because of the general principles of aerodynamics, radiation flow, and so on (as well as historical accidents like the size and orbit of the earth), but in order to predict the weather tomorrow *it may be more useful to think* [emphasis added] about cold fronts and thunderstorms. Reductionism may or may not be a good guide for a program of weather forecasting, but it provides the necessary insight that *there are not autonomous laws of weather that are logically independent of the principles of physics.* [emphasis added] Whether or not it helps the meteorologist to keep it in mind, cold fronts are the way they are because of the properties of air and water vapor and so on which in turn are the way they are because of the principles of chemistry and physics. *We don't know the final laws of nature, but we know that they are not expressed in terms of cold fronts or thunderstorms* [emphasis added]."

In their hearts, most scientists probably believe that there is something both right and wrong about this perspective. I doubt that anyone believes there are laws of nature that magically spring into being whenever we find it convenient to speak in terms of higher-level entities such as cold fronts. Emergence of this sort is what Bedau calls *strong emergence* (see "Background"). Yet concepts such as cold fronts and thunderstorms are so useful that simply to dismiss them as arbitrary though practical constructs seems wrong, too. One way to frame this tension is to pose this question about the ontological status of entities such as cold fronts and thunderstorms. Do they really exist, or are they just conceptual or useful conveniences? In this paper, we propose a perspective in which higher-level entities really do exist, and we provide a physical rationale for this perspective.

We also classify entities. Two are of the most interest:

1. *Mass-based 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 entities, and

2. *Structural/process entities* (the kind 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 feature of nature.* 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.* Entities in both of these classes are self-perpetuating. Although they are not eternal, they are supported by forces that tend to keep them in existence as entities.

BACKGROUND

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, as follows:

- *Nominal emergence* is characterized by 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 some number of 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 the discussion of the designed entity (the house) and symbolic entity (the circle) in the Categories of Entities section.

- *Weak emergence* is characterized by 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 (i.e., they are defined ultimately in terms of lower-level phenomena, 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 does not make this claim) to recursive enumerability (i.e., a property that must be computed to be observed). In particular, since one can simulate a Turing machine in the Game of Life, it can be proved that certain properties of the Game or Life, such as whether the number of live cells is bounded or whether certain patterns will appear, are recursively enumerable but not recursive depending on the starting state of the board.

- *Strong emergence* is characterized by 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. If it were to exist, strong emergence (e.g., laws of weather that are logically independent of the principles of physics) would be emergence that, by definition, is magical,

spooky, and mysterious. From here on, we ignore the possibility of strong emergence.

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. In this paper, we approach the issue of macro vs. micro as one of macro entities vs. their micro components. Our task is to distinguish between (a) macro entities that are composed of micro entity components and (b) simple aggregations of micro entities that do not deserve to be considered (macro) entities.

We say here 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 solely on the components of the aggregation, that property is not emergent. To be emergent, the property must also depend on whatever (if anything) binds the aggregation together. If there are no such binding forces, the aggregation cannot, by definition, have emergent properties.

Here are two 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. (As we will see later, a bag of marbles is what we will call a designed 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 components of an automobile simply as a collection of parts. It has meaning only with respect to the components when bound together as an automobile. (An automobile is also a designed entity.)

This definition of emergence is consistent with Bedau's notion of nominal emergence — which includes weak emergence. The distinction we are making is that a property is emergent when its 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. In particular, 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. 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.

Thus, an automobile is an entity because it has the emergent property of miles-per-gallon.

CATEGORIES OF ENTITIES

It is useful to group entities into categories. Table 1 summarizes our categorization. Mass-based and attractor-based entities are at equilibrium and require no additional energy to persist. Process/structure entities and designed entities are not at equilibrium. Mass-based and process/structure entities are intrinsically bound, being held together by forces internal to themselves. Attractor-based and design entities are extrinsically bound, being held together by forces external to themselves.

Mass-based Entities

A mass-based entity has a mass that is less than the mass of its components. The clearest example is 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 when considered in isolation. As illustrated in Figure 1, a helium nucleus (an alpha particle) has a mass of 4.00153 u, whereas its components, when considered separately, have a total mass of 4.03188 u.

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.

Although the preceding statements 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 that is applied when doing so is retained by the components after the breakup, according to the equivalence of mass and energy and the conservation of mass/energy, the total mass of the components after the breakup must be equal to the mass of the original entity prior to the

TABLE 1 Categories of entities

Does category require energy to be sustained?	Intrinsically Bound Entities	Extrinsically Bound Entities
No. At equilibrium.	Mass-based (e.g., atomic nucleus)	Attractor-based (e.g., lake)
Yes. Far from equilibrium.	Process/structure (e.g., living cell, nation-state)	Designed (e.g., automobile, woven cloth)

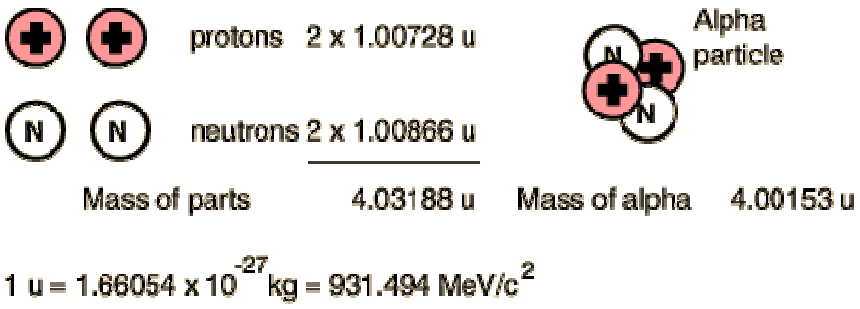

FIGURE 1 Mass of a helium nucleus (Source: Georgia State University, 2004)

breakup 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 a physical aggregation is an entity as the amount of energy required to separate it into its components. "Entityness," at least for physical objects, thus becomes a property with a naively intuitive measure — not a Boolean property.

A Programming Metaphor

As a computer scientist (not a physicist, mathematician, engineer, social scientist, or philosopher), I find it convenient think in terms that can be expressed in programming language constructs. Consider the following object-oriented 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.

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 into the environment. 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 becoming too mystical about it,

this illustrates that emergence (i.e., the emergence of entities), is a fundamental feature of the way the universe works.

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, that defines it. 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 and the previous case, the entropy flow is the same: from the entity to the environment. Of particular interest is that in both cases, no energy is required for the persistence or perpetuation of entities in these classes. Mass-based and attractor-based entities are formed and persist on the basis of primitive forces.

Designed Entities

Designed entities are a structured collection of components that exhibit properties that the components would not exhibit either individually or collectively if they were 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, houses, satellites, and semiconductor chip fabrication facilities. The structures of these entities, if not maintained, typically deteriorate over time — especially though use.

One of my favorite examples of entities in this category is woven cloth, which consists of thread arranged according to a weave pattern. Being essentially a two-dimensional object, cloth has a property (area) that its components (threads, which are essentially one-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

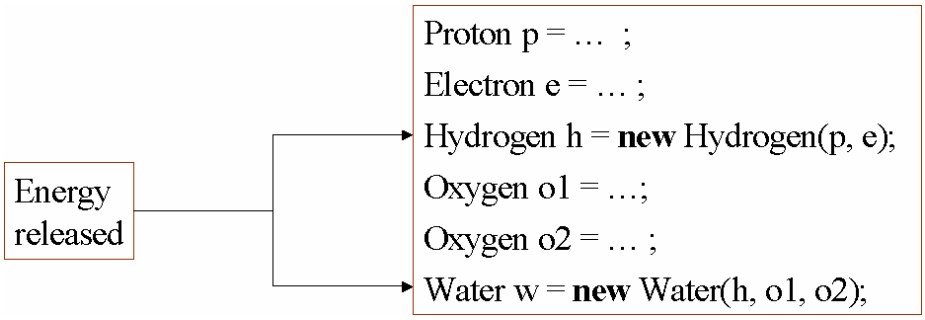

FIGURE 2 Program for building a water molecule

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 cloth is stable if untouched, it may wear, 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.

At the other extreme of sophistication from cloth is a notion that most computer scientists are familiar with: *level of abstraction*. This is the conceptual framework defined by a programming language or computer application program. A level of abstraction is a designed entity or, more frequently, a collection of designed entities along with a collection of operations that may be applied to them. The binding forces that are used to combine lower-level elements into a new level of abstraction are the operations that exist at the substrate level. An executing computer program is the design that combines these lower-level entities into higher-level entities.

In computer science, one typically ignores the need to import energy: the binding forces operate as if they are free once the computer is powered on. When executing a program, a computer reduces the entropy within the computer and expels entropy into the environment as heat.

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, hurricane, and tornado examples below.) The abstract structure that organizes a process/structure entity persists even as the physical material of which the entity is composed cycles through it. Process/structure entities are distinguished by the fact that they tend to be self-perpetuating.

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) by a combination of state law, its articles of incorporation, and its by-laws. The people and property that occupy any particular role in the corporation at any specific time may come and go. It is the formal structure and processes defined by the corporation's charter that persist. (The fact that most articles of incorporation and by-laws 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 and those by-laws that characterize the corporation.)

Most social and biological process/structure organizations are not built in so formal a 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 internal 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 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 designed entities have for external energy (in the form of maintenance) to hold themselves together. The difference is that designed 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 tend to persist if that energy is available (old age is a separate issue) but also depend on the continual consumption of energy to hold themselves together, process/structure entities are what has come to be known as *far-from-equilibrium systems*. These entities are thus self-perpetuating. They are built in such a way that if the environment within which they exist remains relatively stable and if the energy they require to power their internal processes is available, they perpetuate themselves.

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. Here we briefly consider three examples of process/structure entities: hurricanes, fires, and a nation-state.

Hurricanes and Fires

Two nonbiological and nonsocial examples of process/structure entity are hurricanes and fires (or flames). Both extract energy from the environment, which they use to perpetuate themselves and to maintain their internal structures.

A hurricane feeds off the pressure and temperature differential between the warm ocean and dense lower atmosphere and the cooler and less dense upper atmosphere. Here is a description of hurricane formation from the National Center for Atmospheric Research (2004):

> One ingredient [in hurricane formation] is a low pressure area which forms over a large area of warm water. The air being drawn into the central low pressure is curved due to the Coriolis Effect. Surface friction also causes the wind around the low to spiral toward the center. This gives the hurricane a circular rotation. The incoming air must go somewhere so it rises. This rising air, which is saturated with water, cools and condenses to form clouds. The latent heat given off when the water condenses causes the upper air to warm and increase in pressure. This high pressure area is the reason why weather is nice in the eye of a hurricane. This is the start of a feedback mechanism which continues to intensify the hurricane as long as there is warm water from which to draw energy.

Figure 3 illustrates the structure of a hurricane in cross section.

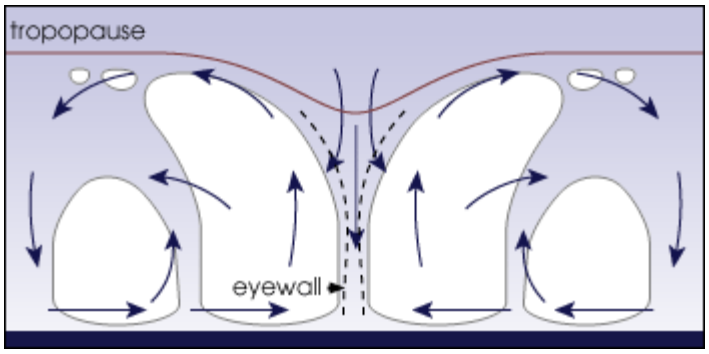

FIGURE 3 Cross-sectional diagram of a hurricane
(Source: NASA, 2004)

Similar (but not identical — typically there is no central downdraft) mechanisms produce tornados, flames, and fire storms. In all cases, energy is necessary to heat the inward flowing air to perpetuate the cycle. A hurricane, or so-called *warm-core* storm, is unusual (as Figure 3 shows) in that the core consists of *downward*-flowing air and the heating takes place in the upper atmosphere as a result of condensation of moisture from the rising moist ocean air. The condensation occurs at the top of a ring around the eye, called the eye wall. This heating causes both increased pressure within the eye and decreased pressure at the top of the eye wall, drawing up more moist air.

What is common to hurricanes, tornados, flames, and fire storms is the operation of a heat engine (i.e., the performance of work, typically the movement of some physical material, through the application of heat energy). A hurricane is unusual in that the heat is generated as a result of condensation in the upper atmosphere, which effectively pumps additional moist air upward into the condensation area.

Hurricanes depend on moist and relatively warm surface air for their self-perpetuation. The environmental energy sources upon which hurricanes depend are (a) the energy that transfers moisture from the ocean to the surface air before it is pumped upward and (b) the continual cooling or dispersal of heat in the upper atmosphere so that the heat generated by condensation does not overly warm the condensation area. With these environmental conditions in effect, hurricanes can perpetuate themselves indefinitely.

The infrastructure of a hurricane consists of the pathways along which air is transported. If these (especially the upflow of moist air) were blocked, a hurricane's internal process/structure would deteriorate, and the hurricane would die.

A hurricane's primary binding force is the physical force that cause gases to move from high-pressure areas to low-pressure areas (i.e., along the hurricane's infrastructure pathways). The binding forces are (necessarily) inherent to the medium (the atmosphere) of which the hurricane is composed. If gases were not subject to pressure differential forces, there would be no hurricane. But because gases are subject to those forces, hurricane structures, once in place, can perpetuate themselves. Other binding forces are those that generate heat as a result of condensation and those that allow air to absorb moisture.

Similar analyses can be done for tornados and, perhaps more interestingly, for fires. 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 persist only as long as such an infrastructure can be built and as long as there is enough fuel to maintain that infrastructure is available.

Nation-State

A nation-state has properties (e.g., capital city, laws, currency, foreign policy) that do not apply to its components; thus, it is an entity. A nation-state has a process infrastructure that provides the means by which it operates as a state and an economy. These include the traditional political and economic infrastructure elements, as follows:

- 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 nation-state's structure and infrastructure that persist over time rather than the elements that play particular roles within the structure.

- No one individual fills a political role indefinitely. (Even kings die, yet kingdoms persist.) It is the political (infra)structure that remains stable, although it may evolve.

- No one truck, road, or airport defines a transportation system, for example. It is the economic (infra)structure that remains stable, although it, too, may evolve.

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

Like a hurricane that develops by using the atmosphere as a substrate, a nation-state (and any social organization) is built by using people as the substrate. Consequently, the binding forces that hold a nation-state together must be operations that people can perform and forces that act on people. The attendees at this conference know far more about this than I. So I will do little more than offer a basic list of capabilities and forces that apply to people.

The capabilities are whatever it is that people are able to do. The analogy to a hurricane is that air is capable of both absorbing and releasing moisture. At their most general scope, the capabilities of people include physical self-propulsion, the ability to understand and use language, the ability to follow instructions, the ability to perform physical acts in the world (e.g., aiming and shooting a gun or digging a ditch), and the ability to manipulate symbols (e.g., voting).

Besides having these capabilities, people are malleable in that they are capable of learning new knowledge, skills, values, and even emotional responses. An extremely important (if seemingly magical) capability — and one upon which a modern market economy (as well as our scientific research infrastructure) relies — is the ability of people to develop new ideas and perspectives. All of these capabilities are available for use in developing a social system.

Besides these capabilities, it is important to catalog the forces that act on people. These include emotional forces (e.g., interpersonal love, tribal loyalty, patriotism, fear, anger, and compassion, which tend to impel people to take actions), physical forces (e.g., being detained, restrained, or killed by force), intrinsic forces (e.g., the need for food, sex, community; the impulse for self-preservation; creativity; taking initiative; ethical behavior), and whatever else is inherent in the nature of human beings.

This is certainly a broad and superficial list, which should be elaborated upon much more carefully. But whatever the list eventually evolves into, it is these forces and capabilities upon which a nation-state must be built.

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 many of the social systems we have created. Perhaps more interestingly, we are also capable of creating the means for creating new entities. Most of the infrastructures of modern nation-states provide a basis for the creation of new entities. The internet is the latest example of such a generic infrastructure around which new entities can grow.

Other Categories of Entities

Besides the categories of entities sketched above, there are a number of other categories of entities that do not fit the preceding paradigm. It is not yet clear how to describe the binding forces for the following classes of entities.

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), or virtually any performance. All of these entities exhibit emergence in that they have properties 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 an emotional) result that differs from the results achieved by the performance of their individual components. Performance entities are different from the descriptions of how they are produced. The performance of a note is not the specification of the note. It is the actual production of the sound. The same goes for the performance of an algorithm or a play.

Two other examples of temporal entities that I do not understand (and that may be related) are a ripple on the surface of a liquid (or more generally, a wave carried by a medium) and the domino effect (e.g., dominos fall in sequence, as one topples the next).

It seems to matter that temporal entities are applied to other entities (i.e., they do not stand alone).

Symbolic Entities

Symbolic entities require interpretation. Examples include a pair of socks,[2] a sentence, the set of prime numbers, the constitution of a government, the specification of an algorithm, and Bedau's circle. All these entities exhibit emergence in that they have properties that their components do not have.

An algorithm (specification) 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. The control structures of an algorithm are not binding forces in the sense used earlier. They do not compel components to stay together.

A sentence has a meaning that depends crucially on its syntax, which binds its components together. The situation is similar to that of an algorithm. But syntax has an effect only in the mind of the interpreter. It is not, in itself, a physically binding force.

Bedau's circle is bound together by its definition (i.e., a set of points equidistant from a distinguished point). Again, the binding structures exist, but they have no force on their own. The definition must be interpreted by an interpreting agent.

In all cases, an interpreter is required for a symbolic entity. Without something to interpret the syntax or other binding connectives of a symbolic entity, it would not exist as an entity.

DOWNWARD CAUSATION

We agree with Weinberg that strict downward causation (macro to micro) is as unlikely as strong emergence. We do not expect new forces to appear magically at a macro level and then have an effect at the micro level. 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 the body of a passenger on an airplane. That trajectory depends on the passenger's mechanical and physiological structure and activities. It also depends on the trajectory of the airplane in which the passenger is riding. That trajectory, in turn, depends on the weather the

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2 An individual sock is a designed entity. It is the pair that is a symbolic entity, with the individual socks as components.

plane encounters during the trip. It also depends on the rotation of the earth, the earth's revolution around the sun, the solar system's revolution around the galaxy, etc. This is a more elaborate form of the example given originally in Sperry (1969): the trajectory of an atom in the rim of a wheel rolling downhill.

Perhaps more interesting, the plane's trajectory also depends on decisions made by the pilot and various flight controllers. These depend, in part, on regulations adopted and distributed (on paper or electronically) by the Federal Aviation Administration (FAA), a governmental entity. The passenger's decision about which flight to book depends on the schedule and rates set by the various airlines, which depends on decisions made by analysts and executives of the airline companies. These scheduling decisions also depend, in part, on regulations promulgated by the FAA, etc.

It would be impossible to compute any of these effects without taking into consideration the entities involved as entities. It would be completely hopeless to attempt to describe all that in a purely bottom-up manner, in terms of the laws of fundamental particle physics.

SUMMARY AND CONCLUSIONS: BINDING FORCES DRIVE EMERGENCE

A property of an aggregate is emergent if it depends on whether and how the aggregate is bound together. Entities are aggregates that have emergent properties. Mass-based entities occur naturally and "for 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 naturally occurring, are not free and exist far from equilibrium. Their persistence and self-perpetuation 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 that often provide a basis for the development of new entities — whose emergent properties sometimes surprise us.

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