Steps to an Ecology of Emergence

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RUNNING HEAD: Steps to an Ecology of Emergence

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Abstract. To begin to take steps to a mental ecology of emergence we first establish two fundamental assumptions from the methodology of transformational grammar—the centrality of human judgment based on direct experience and the proposition that the systematic nature of human behavior is algorithmically driven. We then set a double criterion for understanding any formalism such as emergence: What is formalism X, that a human may know it; and a human, that s/he may know formalism X? In the cybernetic sense, the two are defined in relation to each other. In answer to the first question, we examine emergence as a formalism, using Turing's work as a defining case and an NK Boolean system as a specific working model. In answer to the second question, we frame the knowing of emergence in a Batesonian epistemological approach informed by modern developments in discrete dynamic systems. This epistemology specifies mental process as the transformation of differences across a richly connected network. The relational reference point which integrates the two sides of the cybernetic question is human judgment of perceptual similarity which links emergent hierarchies in a formal NK Boolean model to hierarchies of perceptual similarity based on direct experience.

KEYWORDS: Emergence, Perceptual Categories, Dynamic Constancy, Hierarchies, Boolean Models, Epistemology, Knowledge, Bateson, Kauffman

Steps to an Ecology of Emergence

> I have said that what gets from territory to map is transforms of differences and that these (somehow selected) differences are elementary ideas.
>
> But there are differences between differences. Every effective difference denotes a demarcation, a line of classification, and all classifications are hierarchic. In other words, differences are themselves to be differentiated and classified. In this context I will only touch lightly on the matter of classes of difference, because to carry the matter further would land us in the problems of *Principia Mathematica*.
>
> Let me invite you to a psychological experience, if only to demonstrate the frailty of the human computer. First note that differences in texture are different (a) from differences in color. Now note that differences in size are different (b) from differences in shape. Similarly ratios are different (c) from subtractive differences.
>
> Now let me invite you... to define the differences between "different (a)," "different (b)," and "different (c)" in the above paragraph.
>
> The computer in the human head boggles at the task.
>
> --Gregory Bateson (1972), pp. 463, 464.

Model-based Intuitions about Emergence

In 1952 Alan Turing, in study of embryology, published a groundbreaking paper that laid the foundation for the concept of emergence. Within the constraints of a formal mathematical symbol system, he derived insights into morphogenesis—how form self-organizes from the interactions among well-defined processes. He found that forms observed in nature (dappled patterns, radial whorls seen in leaves around stems) resulted naturally from the interplay of coupled nonlinear equations that in themselves had no hints of the higher order characteristics of the emergent forms. Turning's paper has become among the most seminal of the twentieth century (Keller, p. 108). Fifty years later this insight can now be more easily understood through more accessible formalisms, often derived from the languages of computing (e.g., Holland, 1998, p. 103, p. 125). For example, the gliders generated by simple rules in Conway's cellular automaton, Life (e.g., Holland 1998, p. 138) skate across a computer screen, transforming and reforming as they interact. Gliders have become a canonical example of emergence. Furthermore, simple cellular automaton rules can produce gliders that generate other gliders (see http://llk.media.mit.edu/projects/emergence/index.html).

The distinction between the level of generating processes and the level of wholes that emerge is the basis of the idea of emergent hierarchies. If interacting processes produce wholes with novel characteristics not found in those lower level processes and if the wholes are themselves processes that can interact and so produce even higher level wholes with yet again novel characteristics, then we have an outline of a process for emergent hierarchies. Candidates for emergence were fundamental to Bateson's epistemology (1979, chapter 3), although he did not use that term. The case of difference, that "there must be two entities such that the difference between them… can be immanent in their relationship" (1979, p. 64[4]), is particularly relevant to this discussion. Other candidates discussed by Bateson for what might now be called emergence are binocular vision, beats and moiré patterns.

Boolean Dynamic Systems

To specify how emergent levels develop in a model and, more critically, how those model-defined levels relate to human perception of those emergent levels we will use a computer simulation, E42, which generates NK Boolean dynamical systems (Kauffman, 1993, p. 188). NK Boolean systems are a network of N nodes (the "entities" whose relationship generates difference in Bateson's terms) each of which takes input from K other nodes in the network. These systems are Boolean because each node has only two possible states (0 or 1) and therefore are based on difference. As such, NK Boolean systems create a simulation context which can be mapped to the fundamentals of Bateson's difference-based epistemology (see Malloy, Jensen, & Song, in press). Moreover, E42 is capable of differentiating differences in differences thereby generating emergent model-based hierarchies corresponding to those in the opening quote.

Under very broad constraints the reverberation of differences in NK Boolean networks falls into repetitive cycles called basins or attractors—that is, the system will cycle back to the same overall state in a given number of iterations. The number of iterations in such a cycle is called the basin length. This spontaneous falling into cycles is what Kauffman (1995) calls "order for free." That is, if you grant that biology can be construed as a vast network of transformations of difference, then under certain general conditions it will self-organize into complex cyclic patterns. As Turing demonstrated, these cyclic patterns can be expressed as form; and their emergence from the interactions of lower-level processes is what he meant by morphogenesis.

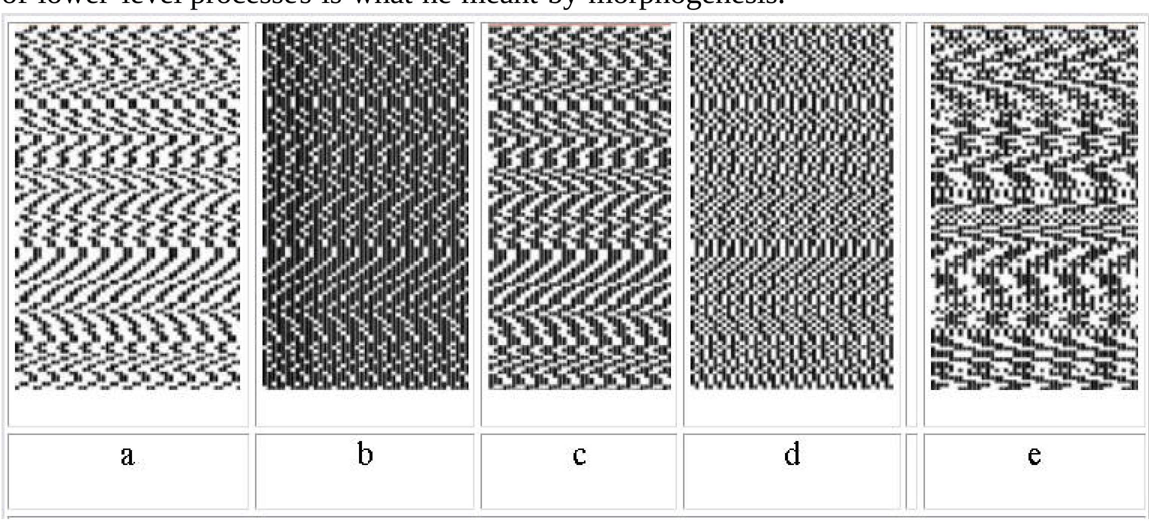


Figure 1. Camouflage-like striped patterns. The first four columns (a to d) are four basins from the same dynamic system. The fifth column (e) is a basin from a different dynamic system.

Figure 1 shows static snapshots of basin patterns from two small Boolean systems generated pseudo-randomly by E42. Note that these patterns are dynamic and result from the system cycling over and over in the same basin. Panels (a) through (d) are all from the same dynamic system. Panel (e) shows a basin from a different pseudo-randomly generated system; panel (e) is included merely to show that there are many pseudo-randomly generated ways to getting the appearance of striped camouflage. Figure 1 shows the sort of camouflage pattern found by Turing but generated from a very different mathematical basis.

This approach to form as a self-organized persistent whole generated by the interplay of underlying processes pioneered by Turing has been a prime basis for defining emergence as a phenomenon and is still consistent with modern criteria (e.g., Holland, 1998, p. 225). Forms, in this tradition, are not things but rather processes, although as with leaf patterns or animal spots, forms may be persistent enough to be taken as if they are things. In fact, as Turing indicated, they are ongoing processes, more like a stationary wave in a mountain stream which may appear to stable, even static, but is in each moment holding its form by the interactions of fluid processes.

Kauffman (1993) proposes that, along with natural selection, the self-organization of emergent form is a co-principle in the evolution of life. As an example of how this might work, note that the forms in panels (a) through (d) in Figure 1 all self-organize from interaction of Boolean processes and are from the same dynamic system. Let these forms represent four kinds of camouflage that self-organize from the Boolean idealization of genetic interaction (Kauffman, 1995, p. 74, 104). Given that these forms can emerge from the interaction of genes, then natural selection, depending on environmental pressures, would act to favor one form over another; the lighter camouflage (a) might be favored in areas with long winters while the zebra-like striping (c) may be favored in open grasslands. If something like the Boolean idealization is what happens in genetic interaction, then the rich patterning observed in life is not the improbable result of chance acting in long random walks of natural selection but the inevitable and expected result of self organization (Kauffman, 1995, p. 71ff). Natural selection, in such a model, has only to explain which form survives; it does not have to explain the genesis of form, which as Turing in 1952 demonstrated, can emerge from process interactions.

Critiques of Emergence

More elusive and more controversial has been the use of these model-generated insights and definitions as explanatory devices for "actual" phenomena. Keller (2002) provides a convincing history of the lack of success in developmental biology of mathematical models in general and of Turing's morphogenic ideas in particular. In short, the contention is that the processes that generate the patterns of hair on a zebra are nothing like the processes underlying Turing's derivations or E42's simulations. That is, the processes which generate levels in a model are sometimes conflated with processes that generate corresponding levels in the phenomena (Goldstein, 2002). Goldstein also summarizes other issues in the definition of emergence. Emergence is often characterized negatively (an emergent characteristic is not found in the processes that generate it). Frequently emergent levels seem arbitrary due to a lack of detailed specification of how processes generate emergent levels; it is one thing to say that cells interact to produce tissues; but without detailed process specification, tissues may be an arbitrarily chosen emergent whole for the interaction of cells. Finally, Goldstein (2002) and others have noted that emergent phenomena of interest arise naturally while models such as glider guns are carefully designed and therefore unlike natural phenomena. We will return to these issues later, after our ideas are more developed.

Intuition as a Legitimate Methodology

We are primarily concerned here with epistemology and with Bateson's notion of ecology of mind. How might hierarchies of differences (see quote which begins this paper) and therefore hierarchies of pattern emerge in a mental system? There are several crucial epistemological frames to establish in answering that question. As a start, our epistemological approach has two fundamental assumptions (Bostic-St. Clair & Grinder, 2001). Both of these assumptions are explicit in Chomsky's transformational grammar.

Let us first focus on the paradigmatic centrality of human judgment based on direct experience (what Chomsky calls intuition). As an example, consider the sentence, "This pig is ready to eat." Is the sentence ambiguous, that is, does it have more than one meaning? Both the answer to that question and the definition of the linguistic phenomenon of ambiguity in Chomsky's paradigm depend on the linguistic intuitions of native speakers of English as they experience that sentence.

The second assumption (also explicit in Chomsky's paradigm) is that human behavior is systematic in the sense of being rule-based; moreover, in the linguistic paradigm, it is assumed that native speakers have internalized the grammatical rules of their native language so that their intuitive judgments are based on these rules. A monolingual speaker of English, while able to make judgments about important linguistic phenomena in English, would fail to do so when presented with Spanish or Chinese sentences. The grammatical rules of a language must be well-learned before a person's direct experience with a sentence leads to appropriate natural language intuitions.

Chomsky's transformational grammar is a mapping from natural language phenomena such as ambiguity onto explicit models, namely, recursive rule systems of great simplicity and formal power. It is worthy of note that learning and internalizing these mathematical rule systems produced model-based intuitions which allowed researchers to determine with little effort what the actual claims of the model are and what would constitute a counterexample to the model's claims so as to make mapping from rule system to linguistic phenomena open to challenge and refinement based on intuition. Notice that there are two kinds of intuitions in this discussion: Those resulting from internalizing the grammatical rules of a natural language and those resulting from internalizing the rules of a mathematical model (which Chomsky then mapped onto the language phenomena). In this epistemological framework, the intuitions about emergence based on Turing's math required a deep commitment to learning the symbolic language system he used. The same is true in the more accessible ideas based on neural nets and their generalization to emergence, (e.g., Holland, 1998). Even the relatively simple logic of a Boolean system (see Appendix) requires a fair commitment to learning its formal language (Kauffman 1993). In any case, intuition, be it based on internalizing grammars or internalizing formal models, is a key element of our epistemology.

In this paper we propose NK Boolean systems as a simple set of recursive rules that generate hierarchies of differences in differences which can be mapped onto visual forms and validated against perceptual intuitions. We will not ask you, the reader, to generate model-based intuitions by internalizing the rules of Boolean math (equivalent to Chomsky's recursive rules); we will, however, ask you to check your natural perceptual intuitions about emergent hierarchies of visual forms (equivalent to linguistic phenomena like ambiguity). If you want to develop model-based intuitions for Boolean systems see Malloy, Jensen and Song (in press) where we lay out the requisite logic of such systems or examine a short summary in the Appendix. Our strategy here is to let computer simulations do the work of realizing the Boolean models' processes by mapping their logic onto visual forms and then allowing you to check your own natural perceptual experience about the emergent hierarchies which result.

The Embodiment of Mind

How can we address emergence within an epistemology soundly rooted in systems framework? Warren McCulloch (1965) suggested a possible direction. The cybernetic conceptualization of neural nets as a basis for mental process was pioneered (Varela, Thompson, & Rosch, 1993, p. 38) by McCulloch & Pitts, 1943. Later, enmeshed in a culture which deeply presupposed the Cartesian mind-body split, in our era manifested as the hidden homunculus of cognitivist theories, McCulloch articulated a general framework for the embodiment of mind (1965). He revised the Psalmist spiritual question, "What is a man that Thou shouldst know him?" to a stringent double criterion (1961): "What is a number, that a man may know it, and a man, that he may know a number?" Here, in this question stated in cybernetic form, a formalism and a description of human epistemology are known in relation to each other. Properly to define emergence by this relational criteria is to propose formalisms for emergence in relation to a description of human knowledge.

McCulloch (1965, p. 6) uses Russell's definition of a number: "A number is the class of all those classes that can be put into one-to-one correspondence with it." As an example, he notes that "7 is the class of all those classes that can be put into one-to-correspondence with the days of the week, which are 7." He further notes that while some mathematicians may question whether this is all that a number means, it is sufficient for his purposes which is to define a number in such a way that, like linguistic ambiguity, most people can have intuitions about it since most people have internalized rules of mathematics well enough to generate intuitions about such a definition of number. For the other side of his question, he refers to his earlier work with Pitts and summarizes the theoretical importance of it. He maps people's intuitions about number onto a recursive rule system of great power. In doing so he lays the ground-work for the now familiar argument that the logic of neural nets is sufficient for knowing in general and for knowing numbers in particular. Both Holland (1998, p. 96ff) and Varela, Thompson, & Rosch (1993, p. 155ff) develop examples of models (neural nets, cellular automata) clearly enough that most people can have model-based intuitions about them.

McCulloch proposed and then met a stringent double standard: He specified a double—(a) a description of what is known (a number) and (b) a model of the epistemology of the knower (neural nets)—in such a way that both terms of the double could be mapped to each other. McCulloch's double requirement that we be explicit about the relationship between a formalism and a description of human knowledge is critical. What are the *processes* which underlie formalism X that it may be known by a human, and the *processes* of human knowing that s/he may know formalism X? To meta-frame this discussion in Turing's metaphor, and to point at what we think

McCulloch and later Bateson were asking us to think about, we ask, "What forms emerge from the coupled interactions of *the above processes*?"

That a Human May Know It

What is the formalism named E42? We will aim here for an intuitive answer to that question. The details of how Boolean systems work along with their correspondences to Bateson's epistemology can be found in Malloy, Jensen and Song (in press). As a start, let us examine how the images in Figures 1 and 2 represent the behavior of E42. Recall that an NK Boolean system consists of N nodes, each taking input from K other nodes. This input consists of either a 0 indicating that the other node is OFF or a 1 indicating that the other node is ON. At any time, T, every node in the system uses a logical operator whose arguments are its inputs to decide if it will be ON or OFF for the next iteration (T+1). For example, if a node has two inputs and its operator is the logical AND operator, then it will be ON during the next iteration (T+1) only if both its inputs are ON during the current iteration (T). If another node is using the logical INCLUSIVE OR operator then it will be ON at T+1 if either one input or the other or both are ON at time T. If a node is using the logical EXCLUSIVE OR (XOR) operator then at T+1 it will be ON if its two inputs are the different (that is, either {0,1} or {1,0}); conversely it will be OFF if its two inputs are the same (that is, either {0,0} or {1,1}). The XOR operator thus detects difference and is related to Bateson's difference-based epistemology in important ways. Any logical operator can be used a system constructed by E42 and which operator actually is used by each node is decided pseudo-randomly when the system is first built. For more details see the Appendix or Malloy, Jensen and Song (in press).

The behavior of an E42-generated Boolean system can be represented as a historical trace of the states (ON or OFF) of all its nodes across time. Examine Figure 2, which has finer detail than Figure 1, and shows output from a different pseudo-randomly generated dynamic system than those that generated Figure 1. This system has N = 35 nodes. The 35 nodes run up vertical axis while time (iterations) runs along the horizontal axis. Look at Figure 2 (a), basin 40. The first column shows the state (ON = black square and OFF = white square) for each the 35 nodes arrayed as a vertical vector. The second column shows the state of each node for the next iteration, and so on. Figure 2 (a) shows one particular basin, basin 40, into which that the system falls. Panel (a) shows 24 iterations on the horizontal axis; this is enough for the system to cycle through "basin 40" four times—that is, the length of the basin cycle happens to be six iterations, and we have four cycles through that basin. Six iterations per cycle times four cycles yields 24 iterations on the horizontal axis of Figure 2 (a). Once in a basin such as that shown in Figure 2 (a) the system will stay there forever unless it is perturbed. Figure 2 panels (b) through (d) show three other basins (each cycling 4 times).

The representation of dynamics as a historical trace generates a pattern resulting from the behavior of a system across time; more specifically, it shows the differences in the states of the full set of nodes (vertical axis) as they change across time (horizontal axis). These changes over time are the dynamic component of system's behavior. The 2-D patterns generated by changes in the states of an array of nodes (ordinate) over time (abscissa) are perceptible to humans as coherent wholes when a system is cycling in a basin. In Figure 1, these patterns are evocative of the visual experience of striped camouflage, and it was this sort of coming-into-being of form a cross time which was the central point of Turing's paper. In Figure 2, the patterns are more abstract.

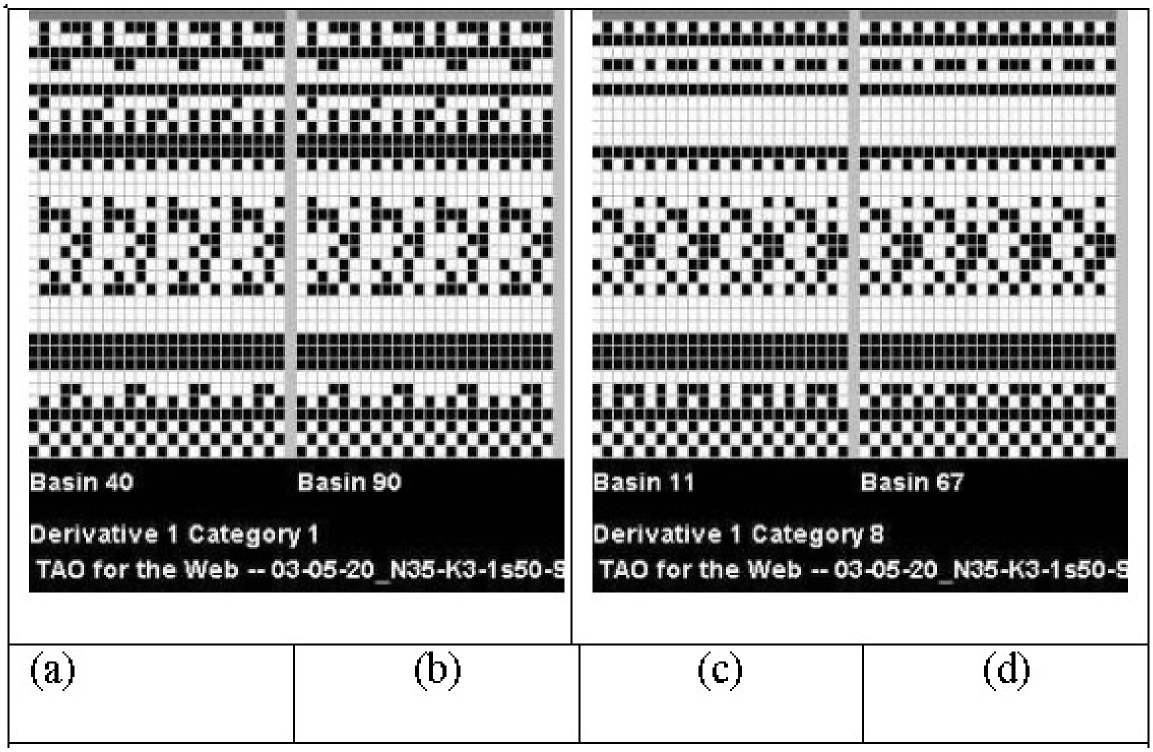


Figure 2. Four basins from a pseudo-randomly generated dynamic system. Panels (a) and (b) are perceived as similar as are panels (c) and (d).

Recall that we described two kinds of intuitions, those that come from internalizing a model (such as Chomsky's) and those that come from encountering phenomena such as linguistic ambiguity. The intention here is to represent the workings of the Boolean model in a way that you may have intuitions from the model without the considerable effort of internalizing its rules. We are examining here the first half of McCulloch's questions: What is (one example, at least, of) a dynamic system that a human may know it? Representing the processes of a Boolean model as a visual historical trace allows you to have visual intuitions about the logic of the model without needing to internalize that logic. On that basis, we will later ask you to check your intuitions about visual hierarchies which are candidates for emergence.

Dynamic Constancies for Differences in Differences over Time

An interesting aspect of Figure 2 is that, in the judgment of humans, patterns generated by basins 40 and 90, panels (a) and (b), resemble each other but are distinct from the patterns of basins 11 and 67, panels (c) and (d), which in turn resemble each other. Here we are using the linguistic methodology and you are asked to examine Figure 2 and make your own judgments.

For a discussion of the nature of emergent hierarchies, these obvious perceptual judgments are crucial. Before we examine that issue, we first will consider one more issue that is technical—the discrete first derivative. The E42 system can perform operations parallel to the thought experiment proposed by Bateson (1972, p. 463, 464) involving hierarchies of difference. Figure 2 shows four basin patterns that result from the historical trace of the differences in a system across time. Change over time implies the possibility of a change in change over time (that is, the discrete analogue of the first derivative). In essence, E42 takes the discrete first derivative to determine whether the differences over time that generate one basin are themselves the same or different than the differences over time that generate another basin. The details of this process are found in Malloy, Jensen and Song (in press).

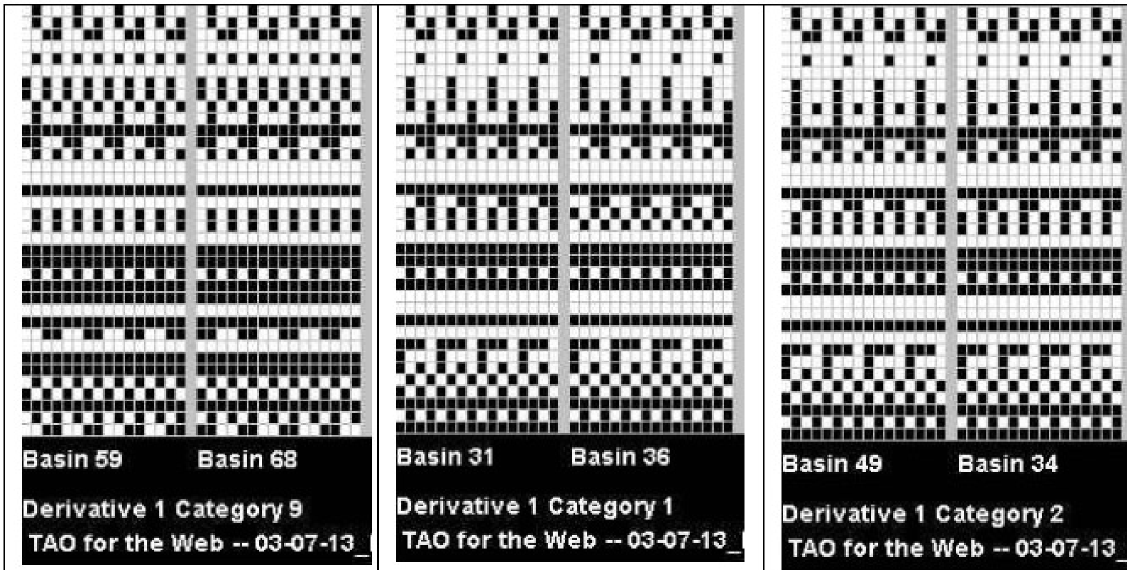
The discrete first derivatives of the basins in Figure 2 (a) and (b) are identical; so too are the derivatives of the basins shown in Figure 2 (c) and (d). That is, the differences in differences over time are the same in panels (a) and (b) and likewise are the same in panels (c) and (d). Patterns that have the same first derivative—panels (a) and (b) or, alternately, panels (c) and (d)—look similar to humans.

Emergent Hierarchies in Model and in Perception

In Figure 2 we have two possible levels of a proposed emergent hierarchy. The first level is realized by the basin patterns (zebra stripes in Figure 1 or the more abstract patterns in Figure 2) that are generated by the interaction of the Boolean processes. This level of emergence is the one proposed by Turing in his study of morphogenesis and is essentially the same level of emergent form as Conway's gliders in the game of Life. The second proposed emergent level is realized by the appearance in Figure 2 of categories of form generated by the model using the first derivatives taken on those forms. In our methodology, these model-generated levels are calibrated against the reader's perceptual judgments.

Figure 3 shows a more interesting example consisting of six basins from yet another pseudo-randomly generated dynamic system that has 36 nodes. The length of a basin in Figure 3 is four iterations; so four times through four iterations yields the 16 iterations shown on the horizontal axis for each basin. Based on identical first derivatives, the model places the six basins into three categories of two basins each: category 9 (basins 59 and 68), category 1 (basins 31 and 36) and category 2 (basins 49 and 34). (The system has more basins and more categories, which are not shown here.) All basins in the same category have identical discrete first derivatives; and all basins in different categories have different first derivatives.

Using the criterion of human intuition akin to the linguistic paradigm you are asked to examine your own perceptual judgments about two interesting perceptual observations with implications for the concept of emergent hierarchies. Both perceptual observations are related to what we will define as the principle of dynamic constancy. First, basins within a category are more similar to each other than they are to basins in other categories; this is the same point noted above in Figure 2. This first point is particularly applicable in category 9 where basins 59 and 68 are perceptually hard to distinguish and in category 2 where basins 49 and 34 are nearly as difficult to distinguish. The only weakening of this point is in category 1 where basins 31 and 36 have some elements that are perceptually quite distinct, distinct enough that some people might not put them in the same category. In fact, there are boundary conditions for this phenomenon (that categories based on first derivatives correspond to human perceptual judgments); these boundary conditions, while important, do not invalidate the phenomenon and are discussed in depth at www.psych.utah.edu/dysys.



First Derivative Category 9	First Derivative Category 1	First Derivative Category 2
Second Derivative Category A	Second Derivative Category B	

Figure 3. Dynamic Constancy. Six visual forms placed into three categories based on identical first derivatives. The three categories are themselves placed into two meta-categories based on identical second derivatives.

Second, and of great interest for conceptualizing emergent hierarchies, is that, taken as a whole, some categories are more similar to each other than they are to other categories. To be concrete, notice that the basins in category 9, while closely resembling each other, are quite distinct from the basins in categories 1 and 2. In contrast, the four basins in categories 1 and 2, taken together, are relatively similar to each other. They certainly resemble each other more than they do the basins in category 9. It is as if there is a possibility of meta-categories consisting of categories that are similar to each other. Could not the four basins in categories 1 and 2 be placed together, all in the same higher-level category? The answer, at least the answer provided by the Boolean model, is yes. How would the model do this?

A first derivative implies a second derivative. Up to this point we have used the first derivative to examine the differences in the differences of the states of a system as it iterates across time. Now we will use the second derivative to examine the differences in the differences in the differences in the states of the system across time. In doing so what we find is that categories 1 and 2 (meta-category B in Figure 3) have identical second derivatives, while category 9 (meta-category A in Figure 3) has a distinct second derivative. This model-based processing of differences in the states of the system over time once again generates categories that correspond to human perceptual judgments.

Now we have three potential levels in a candidate for an emergent hierarchy. The first level is the genesis of form from the interaction of generating processes. The next level is the emergence of categories of form generated by the processes involved in taking differences in differences over time. The third level is the emergence of meta-categories of form based on taking differences in differences in differences over time. These levels, precisely defined in the realm of the model, correspond to human perceptual judgments. We propose that this is one way to operationalize Bateson's hierarchy of differences outlined in the opening quote.

The categories are examples of cases where changes over time themselves do not change. We call the perceptual similarity of patterns in such categories the principle of dynamic constancy and propose it as a new principle of perceptual grouping to be added to the well-known Gestalt principles of grouping (for a modern discussion, see Palmer, 1999).

We have now discussed in general terms what E42 is that a human may know it. The answer, then, to McCulloch's first criterion is that E42 is a formal model whose differences over time generate forms such that the differences in the differences in those forms generate a hierarchy of levels that can be known by humans through judgments of perceptual similarity.

The Human Reference Point

Let us return to our epistemological frame with a quote from Bostic St Clair and Grinder (2001):

> The linguist manipulates the syntactic, phonological, and semantic forms and judges and/or asks native speakers to judge whether the consequences are a well-formed sentence in the language, an ambiguous string or any one of an array of numerous other possibilities. The relevant reference point by the very nature of the research is internal to the bearer of the internal grammar – the native speaker himself.
>
> To put the matter in a somewhat different form, suppose that we succeeded in constructing an instrument that purportedly arrived at the same judgments for visual inputs as those possessed by normally sighted people.
>
> How would we know whether the instrument worked?
>
> The answer clearly is that we would accept the instrument as accurate if and only if the responses of the instrument matched those of normally sighted people. In other words, we would calibrate the instrument by using precisely the same set of judgments (intuitions) reported by the people involved that we presently use in the absence of such an instrument.
>
> Thus in fields where the patterning under scrutiny is patterning of the behavior of human beings, the reference point and the source of the judgments will necessarily be the human being (p. 76).

How could it be otherwise?

In this framework, the correspondence between the hierarchical levels of the model and human perceptual judgments integrates the two sides of McCulloch's relational loop. It is the human that is the relational center when formalisms are generated and known.

What is Human Knowledge that a Human May Know Dynamic Systems?

We now address epistemological issues in the second part of McCulloch's question: What is a human that s/he may know a formalism? We will present one thread of thought in this regard.

The conceptualization of knowledge in terms of the "all or none" character of "difference" goes back in its modern computationally-based form at least to McCulloch and Pitts (1943). The fundamentals of neural nets that they laid down have undergone various stages of elaboration and development by theorists like Hebb (1949), Holland (1975) and Valera, Thompson and Rosch (1993) among many others. And the rigorous focus on difference as the defining epistemological relationship was developed extensively by Bateson (1972, 1979), and continued in our own work by DeLozier and Grinder (1987) with application as a teaching method by Malloy (2001).

Influenced by McCulloch's thinking (see M. C. Bateson, 1991), Gregory Bateson (1979, p.p. 89, 102, 106) proposes that difference is the basis of mental process which itself has six criteria:

> (1) Mind is an aggregate of interacting parts or components. (2) The interaction between parts of mind is triggered by difference. (3) Mental process requires collateral energy. (4) Mental process requires circular (or more complex) chains of determination. (5) In mental process the effects of difference are to be regarded as transforms (i.e., coded versions) of the difference which preceded them. (6) The description and classification of these processes of transformation discloses a hierarchy of logical types immanent in the phenomena.

The second, fourth, fifth, and sixth criteria are particularly relevant to emergent hierarchies of a mental ecology as operationalized here by perceptual categories resulting from the analysis of differences in differences.

McCulloch directs our attention to the relationship between any formalism and the specification of an epistemology within which that formalism could be known. Bateson's descriptions of mental process, connected as they are to McCulloch's foundations of neural network theory, act as a starting point for an epistemology that would allow humans to know emergent phenomena. Based on that starting point we have given Bateson's descriptions more specificity by modeling them with a Boolean system. This modeling allowed the specification of what is meant by taking differences in difference and produced model-based hierarchies of visual pattern. This model-based hierarchy in turn corresponds to human judgments of similarity—the reference point for connecting model-based emergent hierarchies with emergent hierarchies in perception.

Critical Concerns Revisited

Earlier, we focused on three critiques of emergence as a concept. One is that the processes that underlie hierarchies can be under-specified, vague and post hoc with the result that the emergent levels which are named are arbitrary. In the case of the perceptual categories presented here, the Boolean generating processes, including discrete derivatives, produce hierarchies in the visual output of E42 model that are well-specified, thus the model-based categories which emerge are not arbitrary but a deterministic result of Boolean logical processes. The second critique is that the levels in model and the levels in the actual phenomena are conflated and then the processes that generated the emergent levels in the model are assumed to be the same as the processes that generate the levels in the actual phenomenon. This is a deeper scientific issue, applying to all models and theories whether they address emergence or other concepts. It amounts to confusing the map with the territory. In our case this would be equivalent to assuming that the transforms of differences generated the E42 model are the same as the transformations taking place in a human perceptual system which generate corresponding levels of similarity judgments. This critique cannot, indeed should not, be dismissed in any definitive sense. It is crucial to keep a well-defined distinction between, on one hand, a model, and how it works, and, on the other hand, the phenomenon, and how it works.

A productive and positive approach to this second issue is offered by Bateson (1979, p. 76) who defines explanation as the mapping of a tautology onto a description of some phenomenon. Bateson considers such a mapping from tautology to description as an example of the gains in knowledge that result from multiple versions of the world. What we have offered here is a (Boolean) logical tautological system mapped onto Bateson’s description of a hierarchy of differences which opened this paper. The intent is not to confuse the tautology with Bateson’s descriptions nor with the processes of human perceptual physiology. Rather the intent is to generate gains in insight and utility that could result from putting the two into relationship, much in the spirit of McCulloch double-sided question. Thus the formal hierarchies of emergence based on differences in differences in the model are set into relationship with a Bateson’s description of a human as knower; and, finally, human perceptual judgments are used as the reference point for evaluating the utility of that relationship itself.

The third critical concern was that emergent phenomena of interest arise naturally while models are carefully designed. Taking Bateson’s framing of explanation as a mapping of a tautology onto a description of a phenomenon this will always be the case. Verbal or mathematical, the model or the theory that we map onto our descriptions of the world are by definition a human artifice. The hope is that some utility emerges from such mapping from artifice to nature. In this discussion hierarchies of differences in differences generated by E42 have been mapped onto visual form and hierarchies of perceptual similarity in those forms. The utility of gliders and glider guns in cellular automata theory depends on what they are mapped onto and how the mapping is done. But even if gliders are taken as a general metaphor, they may be of great value.

Emergence as Metaphor

The importance of metaphor’s function in a mental ecology is both pervasive and useful. An important metaphor, at least in western civilization, which is proper to religion and certain areas of philosophy and metaphysics, is the designer metaphor—that an all-knowing, all-powerful being designed the universe. Something, split off from and separate from the biological world, designs the biological world. Proper as it may be in religion and other disciplines, the designer metaphor is not proper to science. Turing set out to defeat the “argument from design,” in the life sciences. The concept of emergence which his work eventually led to is a powerful metaphorical alternative to the metaphor of designer. In this function it allows discourse about many human ideas and experiences without the necessity of proposing a designer. Keller (2002, p. 90) documents that Turing intended for once and for all to “Defeat the argument from Design.” He provoked an alternative framework to theories and discourses that presupposed life needed ultimately to be explained by a designer. As we’ve argued in the previous section, there is no paradox here; a mathematical proof that form can emerge from the interplay of processes is no more paradoxical in its use as a tautology to map onto natural phenomena than are other tautologies, whether they be the idea of a designer or idea of reductionist causality (see below).

The power of the emergence insight is that wholes self-organize themselves as a natural function of the interplay of the processes that make them up. Turing and others have, at least within the realm of logic and mathematics, offered proofs of this. This is a logico-mathematical concept of great generality and power. Science doesn’t follow the chain of causality back to the being, who external to the world, designed and created the world. It does use, however, a reductionist metaphor to follow causality down to sub-atomic particles or back through time to the big bang. While such chains might well someday be literal, tracing every link rigorously, in fact currently that is not possible; and the reductionist chain is primarily metaphorical, coloring in the background the way we think about what is important in theory and data. The metaphorical frame of emergence offers an alternative background, supplanting long chains of metaphorical reductionist causality with local neighborhoods of process levels within which phenomena of interest self-organize into emergent wholes to be studied and understood in relation to those neighborhoods of process. As Keller (2002, p. 102) summarizes it, “Turing’s work… offered a way out of the infinite regress…” In fact, within the emergence metaphor, the reductionist chain can never be complete because there will always be gaps in that chain where sub-processes self-organize into higher-level processes whose characteristics cannot be found in the sub-processes.

As Kauffman argues, the underlying concepts of science influence scientists and nonscientists alike every day in metaphorical ways.

> The vast mystery of biology is that life should have emerged at all, that the order we see should have come to pass. A theory of emergence would account for the creation of the stunning order out our windows as a natural expression of some underlying laws. It would tell us if we are at home in the universe, expected in it, rather than present despite overwhelming odds (Kauffman, 1995, p. 23).

In a general day to day context, having a way of understanding that leaves can form in an elegant whorl around a plant’s stem as a natural consequence of the processes of plant physiology or that organs might emerge out of tissues and tissues out of cells is a useful alternative both to thinking about life as designed by an external entity and to thinking in the materialist tradition of biology as a machine, a linear sequence of cause and effect. If formalisms, such as numbers, emerge as characteristics of neural networks, then, by metaphorical generalization, mental processes, ideas, the whole of mental ecology can be cast as an emergent characteristic of the processes of human (and all) biology—mind and body are an integrated whole. And they are integrated as a whole both in a metaphorical way and in a way that is susceptible to study through formal models, in whatever degree of specificity is required by a scientific question. They are integrated in a way which is "neither mechanical nor supernatural" (Bateson and Bateson, 1987, chapter 5). As such, the metaphor of emergence serves as a functional addition to the mental ecology of western society, with potential for contributing to integrating the mind-body split and moving toward mind and nature as a necessary unity (Bateson, 1979).

A final gain of great potential value which results from using dynamic systems tautologies like E42 to map onto descriptions of knowledge is that in a dynamic systems approach mental process will self-organize. If "ideas" are thought of as dynamic basins, then knowledge need not always be learned incrementally; rather, interactions with the environment within such a model are likely to provoke mental process to self-organize into ideas. The flash of insight is what is expected and works hand in hand with incremental learning. Insight and incremental learning might correspond in a general way to the modern insight that evolution is shaped by both self-organization and by natural selection.

Steps to an Ecology of Emergence

How might hierarchies emerge in a mental ecology? To answer that question we have used McCulloch's double criteria: What is emergence, that humans may know it, and human knowledge, that they may know emergence? In the cybernetic sense, the two are defined in relation to each other. In answer to the first question, we have examined emergence as a formalism, using Turing's work as a defining case and an NK Boolean system as a specific working model. In answer to the second question, we have framed the knowing of emergence in a broad Batesonian epistemological approach informed by modern developments in neural nets and discrete dynamic systems models. This epistemology specifies mental process, both verbally and in computer simulations, as the transformation of differences across a richly connected network. As the relational reference point which integrates the two sides of McCulloch's cybernetic question, we have used human judgments of perceptual similarity to link emergent hierarchies formally found in an NK Boolean model to hierarchies of perceptual similarity in human knowledge.

APPENDIX

E42 builds Boolean systems consisting of N (4 = N = 400) binary nodes (0, 1). On any iteration (T), each node accepts input (either 0 or 1) from K (2 = K = 5) other nodes in the system. Let the Boolean value "1" mean a node is "ON" and "0" mean a node is "OFF." Each node has a logical truth table which determines what its value will be on iteration T+1 as a function of the inputs it receives on iteration T. **NODES**. Consider as an arbitrary example a minimal system that has N=4 nodes and K=2 inputs to each node. Name the four nodes, in order, A, B, C, D. **WIRING**. Let node A take input from nodes C and D; let B also take input from C and D. Let nodes C and D each take input from nodes A and B. **LOGICAL OPERATORS**. Node A uses an *OR* gate to determine if it is ON at T+1; that is, it will be ON at T+1 if either C or D or both are ON at T. Node B uses an *EXCLUSIVE OR (XOR)* gate; that is, it will be ON at T+1 if either node C or node D (but not both) are ON at T. Node C uses an *AND* gate; that is, it will be ON at T+1 only if nodes C and D are both ON at T. Node D uses an OR gate. The operators in this example are arbitrary. **STATE VECTORS**. To keep track of the changing states for all four nodes we define a state vector. At time T, the state vector, **S**(T), is defined such that the first position in the vector represents the state of A, the second position the state of B, and so on. In this way the expression **S**(1) = {1100} means that, at time T=1, A = 1, B = 1, C = 0, and D = 0. Define a state space as a matrix of all possible state vectors; in this example the state space is the set of vectors from {0000} to {1111}. **STATE TRANSITIONS**. As a dynamic system, the system's state vectors can change over time (T). These changes are deterministically derived from the wiring and logical operators of the system. For example, if at T the system is in state vector {1000}, where only node A is in state 1, then at T+1 the system will go to {0001} where only node D is in state 1, where 1 = ON. This transition can be derived using the logical operators acting on inputs. Given {1000} at T, at T+1 node A will change to 0 (since nodes C and D are both 0 at T). On the other hand, node D will change from state 0 at T to state 1 at T+1 because D takes on state 1 if either A or B or both are a 1, which is the case at time T. By similar reasoning, nodes B and C do not change states. Other state transitions are left to the inspection of the reader. For convenience, we list all state transitions: {0000} => {0000}; {0001} => {1100}; {0010} => {1100};{0011} => {1000};{0100} => {0001};{0101} => {1101};{0110} => {1101};{0111} => {1001};{1000} => {0001};{1001} => {1101};{1010} => {1101};{1011} => {1001};{1100} => {0011};{1101} => {1111};{1110} => {1111};{1111} => {1011}. **BASINS**. From this list of all possible state transitions we can start the system in any state vector and follow the flow of its deterministic process from one state vector to another. For example, starting with vector {0111}, we find the following flow: {0111} => {1001} => {1101} => {1111} => {1011} => {1001)… Note that {1001} has now repeated; therefore the system will loop back to {1001} every four iterations, cycling endlessly through {1001} => {1101} => {1111} => {1011} => {1001}... This is called an attractor cycle or basin of length 4. Call this Basin 1. The first vector in this example, {0111}, is called a tributary because if the system falls into that vector it will only pass through it once on its way to Basin 1. Basin 1 has four other tributaries: {0101}, {0110}, {1010}, {1110}. The reader can confirm that this minimal system has two other basins. Basin 2 = [{0001} => {1100} => {0011} => {1000} => {0001}...]. Basin 2 has two tributaries: {0100}, {0010}. Basin 3 = [{0000} => {0000} => …]. External or internal "perturbations" are required to provoke the system to escape from a basin. In confirming the above logic, we recommend that the reader create truth tables for the logical operators, make a table of state transitions, and visualize both the wiring and the basin structure with sketches.

References

Bateson, G. (1972). *Steps to an ecology of mind*. Chicago: Chicago University Press.

Bateson, G. (1979). *Mind and nature: A necessary unity*. Cresskill, N.J.: Hampton Press.

Bateson, G. & Bateson, M. C. (1987). *Angels fear: Toward an epistemology of the sacred*. New York: MacMillan.

Bateson, M. C. (1991). *Our own metaphor*. Washington, D. C.: The Smithsonian Press.

Bostic-St. Clair, C. & Grinder, J. (2001). *Whispering in the wind*. Scotts Valley, CA: J & C Enterprises.

DeLozier, J. & Grinder, J. (1987). *Turtles all the way down*. Grinder, DeLozier Associates. Bonny Doon, CA.

Goldstein, J. (2002). The singular nature of emergent levels: Suggestions for a theory of emergence. Nonlinear Dynamics, Psychology and Life Sciences. 6, 293-309.

Hebb, D. O. (1949). *The organization of behavior*. New York: John Wiley & Sons.

Holland, J. H. (1975). *Adaptation in natural and artificial systems.* Ann Arbor, MI: University of Michigan Press.

Holland, J. H. (1998). *Emergence: From chaos to order*. Reading, MA: Addison-Wesley Publishing.

Kauffman, S. A. (1993). *The origins of order: Self-organization and selection in evolution*. Oxford: Oxford University Press.

Kaufman, S. A. (1995). *At home in the universe: The search for the laws of self-organization and complexity.* Oxford: Oxford University Press.

Keller, H. F. (2002). *Making sense of life.* Cambridge, MA: Harvard University Press.

Malloy, T. E. (2001). Difference to Inference: Teaching logical and statistical reasoning through online interactivity. *Behavior Research Methods Instruments & Computers*, 33, 270-273.

Malloy, T. E., Jensen, G. C., & Song, T. (In press). Epistemology and evolution: Expressing Bateson's epistemology with Boolean networks. *Nonlinear Dynamics, Psychology, and the Life Sciences*.

McCulloch, W. S. (1961). What is a number, that a man may know it, and a man, that he may know a number? *General Semantics Bulletin*, nos. 26, 27, pp. 7-18.

McCulloch, W. S. (1965). *The embodiment of mind*. Cambridge, MA: The MIT. Press.

McCulloch, W. S., & Pitts, W. H. (1943). A logical calculus of the ideas immanent in nervous activity. *Bulletin of Mathematical Biophysics*, 3, 115-133.

Palmer, S. E. (1999). *Vision Science: Photons to phenomenology*. Cambridge, MA: The MIT Press.

Turing, A. M. (1952). The chemical basis of morphogenesis. *Philosophical Transactions of the Royal Society of London. Series B, Biological Sciences*, 237, 37-72.

Varela, F. J., Thompson, E., & Rosch, E. (1993). *The embodied mind*. Cambridge, MA: MIT Press.

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4. Page numbers for Mind and Nature refer to the 2002 Hampton Press edition.