

Emergence: From Chaos to Order

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BEFORE WE PROCEED

Emergence: much coming from little.

Dynamic: they change over time. Though the laws are invariant, the things they govern change. The rules or laws generate the complexity, and the ever-changing flux of patterns that follows leads to perpetual novelty and emergence.

The Greeks set forth the idea that all machines can be constructed by combining (copies of) six elementary mechanisms (the lever, the screw, the inclined plane, the wedge, the wheel, and the pulley).

Persistent patterns at one level of observation can become building blocks for persistent patterns at still more complex levels.

Here we come upon a central point about model building, innovation, and the study of emergence: building model, or developing a theoretical constructs in science hides the earlier, metaphor-driven models that lead to the constructs.

Mechanisms (building blocks, generators, agents) and perpetual novelty (very large numbers of generated configurations).

Dynamics and regularities (persistent, recurring structures or patterns in generated configurations).

Hierarchical organization (configurations of generators become generators at a higher level of organization).

Herein lies a major value of models: we can anticipate consequences without becoming involved in time-consuming, possibly dangerous, overt actions.

A (model is) a tentative ideational structure used as a testing device.

GAMES AND NUMBERS

The central nervous system (CNS) consists of cells called neurons. When a neuron is sufficiently stimulated, it fires, producing an electrical pulse that goes out over a long extension of the neuron called an axon. This axon forms contacts, called synapses, with many other neurons. When a pulse arrives at the synapses, it stimulates the neurons contacted. If enough pulses arrive at the synapses on a neuron's surface within a short time interval, that neuron in turn fires. If one traces a sequence of connections in the CNS, that sequence is quite likely to form a loop that returns to the origin of the sequence. That is, the neuron at the start of the sequence originates a chain of pulses that eventually feed back to restimulate the originating neuron. This feedback can make loops of connections reverberate – a kind of “ringing” – without further stimulation. As a result, the central nervous system is continually ablaze with activity, multitudes of pulses circulating even during deep sleep and unconsciousness.

MAPS, GAME THEORY, AND COMPUTER-BASED MODELING

The object in constructing a dynamic model is to find unchanging laws that generate the changing configurations. These laws correspond roughly to the rules of a game. In a game, the rules say how the configurations (states) change as different moves are made; the players affect the course of the game by choosing moves.

To build a dynamic model we have to select a level of detail that is useful, and then we have to capture the laws of change at that level of detail.

1. Defining the model's states.
2. Define the laws of change that work at this level.

The transition function assigns to each state the state that will occur next under the laws of change. Where the course of change of the system can be affected from “outside” – where the system can receive inputs from the outside – the transition function provides a different correspondence for each input to each state.

CHECKERS

Failed predictions can serve as well as overt reward as a basis for improvement. Adjustments made only on the basis of reward lose information acquired en route. Predictions made along the way, on the other hand, make it possible to use interim information to improve performance.

TOWARD A GENERAL SETTING

1. Model the world
2. Each model consists of multiple interacting copies of a limited number of pieces, particles, or components (types).

3. The configuration of the model's components changes as time elapses. With careful modeling, the particular configuration of the components at any time fully determines what can happen next.
4. Interactions are constrained by a succinct list of rules (equations). All possible state (configuration) sequences are the outcomes of a succession of limited rearrangements specified by these rules.

Technically these interactions, and the resulting system, are nonlinear: The behavior of the overall system cannot be obtained by summing the behaviors of its constituent parts. We can no more truly understand strategies in a board game by compiling statistics of the movements of its pieces than we can understand the behavior of an ant colony in terms of averages. Under these conditions, the whole is indeed more than the sum of its parts. However, we can reduce the behavior of the whole to the lawful behavior of its parts, if we take the nonlinear interactions into account.

One recurring theme is essential to emergence: in each case there is a procedure for freely generating possibilities, coupled to a set of constraints that limit those possibilities.

State: The state of a system, when properly defined (whether for games, neural nets, or physics), subsumes all aspects of past history that are relevant to future possibilities.

Rules (generators). It is the thesis of this book that the study of emergence is closely tied to this ability to specify a large, complicated domain via a small set of "laws".

Agent: all are described in terms of rules or laws that determine their behavior in a larger context. In each case we can describe these agents as processing material, energy, or information to produce some action which is usually the transport of material, energy, or information. More generally, we can talk of an input state being processed to produce an output state. The input state is determined by the immediate environment of the agent, and the output state determines the agent's effect on its immediate environment.

The path to constrained generating procedures involves the following steps.

1. Translate the notion of rule (for instance, the rule for jumping in checkers, or Hebb's rule) into the notion of mechanism.
2. Define ways of linking mechanisms together to form networks. The setting must make evident how the actions of one mechanism can affect others
3. To define the state of a whole cgp in terms of the states of the component mechanisms.
4. Provide a specific procedure in cgp's for defining hierarchies of subassemblies, using more complex mechanisms built up from the basic mechanisms.

VARIATION

A cgp can change its own connections only if it has mechanisms, called processors, that can modify other mechanisms. A processor's transition function must accept other mechanisms as inputs, and its output must be in turn be a mechanism. We can simplify the formalism if we design the transition function to process descriptions of mechanisms, rather than the mechanisms themselves. It is as if the transition function is fed designs as inputs, producing a new design in response (implementation is assumed to be automatic once the design is available).

We can think of the id tag as a kind of address, which allows other mechanisms to access the given mechanism by knowing its associated tag.

To use this address, each input of each mechanism now has an associated condition that designates the tags of the mechanisms it will accept as input. The condition is a kind of filter. It looks over the n mechanisms in the cgp- v and decides which if any are suitable for that input; a mechanism is suitable if it has an id tag that is acceptable to the condition. Specifically, the condition is used as follows:

1. If there is no mechanism having an id tag that meets the condition, then the input is free its values must be specified from outside the cgp- v as in the case of a free input in a fixed cgp.
2. If there is exactly one mechanism with an id tag that meets the condition, then the input is "connected" to that mechanism the letter in the alphabet corresponding to the mechanism's description becomes the current value of that input.
3. If there is more than one mechanism with an id tag that meets the condition, then one of the mechanisms is selected at random (each time) to be connected to the input, the input value being determined as in 2.

The augmented mechanisms we're dealing with have the following standard parts:

1. an id tag:
2. a set of inputs, each with an input alphabet and an associated condition:
3. a transition function that uses the inputs and a set of internal states as arguments.

The descriptions are reasonably compact. For instance, if the indices are 3 bits long (allowing 8 transition functions), and the id tags are 10 bits long (1,024 distinct tags), then the conditions will be described by strings of 13 letters, and the overall description (when there are two conditions,) will be 39 letters long.

The condition part of each input of each mechanism on the current-state list is checked against the other entries on the list.

The trick is to tune the cgp to highlight questions about emergence. We need to pick generators and constraints that offer a feasible approach at the right level of description. The insights that lead to these interesting choices often depend on a careful use of metaphor and cross-disciplinary comparisons.

Just what is a new level in a cgp? The answer turns on one of the basic properties of a cgp: the possibility of combining mechanisms to make a more complex mechanism. We started the definition of a cgp by characterizing each component mechanism in term of a set of states S , a set of inputs I , and a transition function f , that specifies the way in which the mechanism's current input and state determine its next state. The cgp itself is formed by interconnecting these mechanisms. The objective now is to show that the resulting composite, the resulting cgp, can itself be characterized as a mechanism a subassembly that can be used to form still more complex mechanisms.

The almost automatic instinct of a scientist is to try to redescribe the states in terms of more elementary components, with the objective of finding components and interactions that are simpler to describe than the original.

A metaphor also involves a source and a target.

SELECTION OF BUILDING BLOCKS

To a large degree that is what study of a discipline is all about: the acquisition of the building blocks and associated techniques of that discipline. If we are studying physics, we learn about motion, mass, and energy and the forces that transform them; we also learn associated tools like the differential calculus. If we are studying poetry, we learn about rhyme, meter, tropes, and standard organizing forms such as ode, sonnet, or haiku; we also learn critical tools to test our ideas and inventions. All disciplines have similar requirements.

IN BRIEF

Framed in terms of our general setting, come two major steps: (a) discovery of relevant building blocks, and (b) construction of coherent, relevant combinations of those building blocks.

Once a set of building blocks has been chosen, innovation depends on selection from among the plethora of potential combinations. The possibilities are so numerous that the same building blocks can be used over and over again without seriously impairing the chances for original discoveries. Think of the standard building blocks provided by words in a language, or fold themes in music. The key to handling this complexity is the discovery of salient patterns in the tree of combinations. Creative individuals exhibit a talent for such selection, but the mechanisms they employ are largely unknown.

It is a matter a speculation, but worth examining, that the mechanisms of selection in the creative process are akin to those of evolutionary selection, simply running on a much faster time scale. Even something as simply running on a much faster time scale. Even something as simple as a speedup can revise a model to the point of changing our outlook. A lapse-frame movie of a wild grapevine moving up a tree looks remarkably purposeful. A lapse frame animation of geological evolution shows the fluid, responsive, coherent movement of clouds in the sky. A lapse frame animation of the evolution of some family of organisms would almost certainly show the tentative probes, withdrawals,

redirections, and cumulative construction we associate with creative activity. In both evolutionary and creative exploration we encounter patterns and lines of development (strategies) that emerge under selection. And in both cases emergent building blocks propagate their effects in cumulative ways, through recombination and interaction. We've already seen several examples of this propagation in their earlier discussion of reduction (chapter 10), and more detailed discussions of the mechanisms are given in Hidden Order. There is much to be learned, I think, by modeling cognition via a translation of the mechanisms of natural selection, mimicking Maxwell's translation from gears to fields.

CLOSING

Chapter 12

I'd have to employ a more intricate formal apparatus to express them.

Synthesis

It is these derived consequences, when theory is successful, that suggest new kinds of observations.

The essence of model building is shearing away detail, but the apparatus of experimental design moves concentration in the opposite direction.

Emergence-Next Steps

I think a minimum of three levels will be necessary to arrive at a representative body of theorems relevant to emergence: mechanism-agent-aggregate. Formally, we might consider only two levels, treating all higher levels as recursions of these basic relations.

It is particularly important that the theorems delineate the (new) constraints imposed by the aggregate on the individual agents.

The emergence of overlaid generating systems is a critical feature that does not fit into the formalism of traditional system theory. Yet, as we've seen, such an overlay can completely divert the system from its previous course. The transition from the world of individual craftsmen to the world initiated by Adam Smith's pin factory lies beyond the ken of traditional dynamics. Add to this the tremendous increase in range that occurs each time a new building block (the transistor, for instance) is discovered. A theory of emergence must offer insights into these processes and suggest conditions that enhance or suppress their occurrence.

Model as Guides

Use of computer-based models in exploration.

The Baconian approach of gathering data until significant relations emerge is unlikely to work because systems exhibiting emergence are so complex. In particular, nonlinear interactions almost always forestall the simple parsings, such as regressions, that can reveal causal relations.

Assure emergence.

At the broadest level, this book's thesis has been that models and model building underlie much, perhaps most, human intellectual endeavor. At every point along the way, we have encountered models, ranging from early games to rigorous mathematical models and, more recently, computer-based models. We have discussed the relationship between target and source models as a way of understanding the kinds of reduction that are so productive for science. Above all, we've seen that models give us a way of compensating for the perpetual novelty of the world.

Control and Prediction

It is not common, but it is important, to allow those same directors to see and manipulate the mechanisms and interactions underlying such models, using their intuition to move the models into plausible regimes. When this is possible, the model often reveals certain disastrous "cliffs" that appear and reappear under a wide variety of assumptions.

Innovation and Creation

Ultimately, significant innovation depends on the "long line": the ability to go beyond cut-and-dry recombinations of well-known building blocks to the more distant combinatorial horizon.

"Getting more out than you put in"

Emergence, then, is a matter of macrolaws and the overlaid constrained generating procedures that result. A detailed knowledge flexibility of the ant colony. The capabilities of a computer program are hardly revealed by a detailed analysis of the small set of instructions used to compose the program. We will soon know the complete set of genes (or at least some of the alleles of each gene) coded in human DNA, but we will be far from understanding the program those genes specify – the program that takes a fertilized egg to the complicated 100 billion cell mature organism.