Complex Adaptive Systems and Spontaneous Emergence

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Abstract. This paper introduces concepts associated with complex adaptive systems (*cas*), linking those concepts at some points to economic planning. The paper begins (section 1) with an informal description of the notion of a *cas* and then (section 2) discusses the critical role of "building blocks" in understanding *cas*. Using these ideas, the paper goes on (section 3) to discuss the phenomenon of "emergence", wherein the whole of the system's behaviour goes beyond the simple sum of the behaviours of its parts. The body of the paper (sections 4 through 6) looks at the role of modelling in predicting the behaviour of *cas*, examining the kinds of model that will serve this purpose. The paper concludes (section 7) with a brief discussion of the relevance of these ideas to economic planning.

1. Complex Adaptive Systems

A complex adaptive system (*cas*) exhibits three distinguishing characteristics:

(i) A *cas* consists of a large number of interacting components, usually called *agents*. The agents may range from firms in an economy or participants in a market to antibodies in the immune system or signalling proteins in a biological cell.

(ii) The agents in a *cas* interact in non-additive (non-linear) ways. The interactions can be specified by associating a set of condition/action rules with each agent, where each agent's rules describe its strategy for interacting with other agents (the counterpart of a strategy for playing a game like chess). Such rules range from a simple stimulus-response form, IF stimulus x THEN make response y, to message processing rules, IF message x THEN send message y. Because message processing rules can implement any program that can be written for a general-purpose computer, this way of specifying interactions is fully general. Often, the rules are organized to form an internal model of the agent's external world, allowing the agent to anticipate the future.

(iii) The agents in a *cas* adapt or learn. That is, they modify their rules as experience accumulates, searching for improvements. Learning to play a complicated game, such as chess, provides an example: as one learns to play, some rules begin to implement sub goals ("develop your pieces during the opening stages") and look ahead ("if I move that bishop, I will lose a

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rook to a knight's fork three moves from now"). As we will see (section 2) discovering new, plausible rules depends upon finding appropriate "building blocks" for describing parts of the *cas* agents.

2. Building Blocks

Building blocks are the pervasive, critical foundation of an ability to act with insight in a complex world. Human perception, for example, consists primarily in combining well-known, simple components to describe familiar phenomena. Different trees are described by different arrangements of familiar parts: leaves, stems, branches, and trunks. Similarly, human faces are composed of variants of standard parts - hair, forehead, eyebrows, eyes, nose, and so on. A little thought shows that we approach all objects, familiar and unfamiliar, via combinations of familiar building blocks.

We can also extract building blocks as the generators of the dynamic situations that characterize the interaction of agents. Consider the rules of chess: the rules are building blocks that generate a miniature artificial world in which two agents interact. Though chess is simply defined - less than a dozen rules suffice - it is an artificial world of perpetual novelty. We never see the same game played twice unless some previous game is deliberately recorded and repeated. The game is so complex that, after centuries of study, we have no idea of what a "best strategy" would be for playing the game. Nevertheless, in this perpetually novel world, planning and anticipation are possible, indeed essential.

Planning in chess depends upon extracting and exploiting certain patterns (configurations of pieces) that occur repeatedly in the play of the game. These patterns become higher-level building blocks from which to construct strategies (plans) for playing the game. Over the centuries, chess players have repeatedly discovered new repeating-pattern building blocks that make possible ever more sophisticated strategies. For example, early in the 20th century, chess players discovered that certain interlocking pawn structures could exhibit strong influence on the play of the game. As a result the pawns in today's game do a lot more than they did in the 19th century. By adding this pawn-structure building block to the repertoire, a present-day master chess player can easily outplay a 19th century player of equal rank.

Lest this discussion of games seem frivolous, note that the rules of a game are not different in kind from the axioms that generate Euclidean geometry, or the set of computer instructions that define a flight simulator for a new aircraft. Indeed if we look to that most complex of organizations, the biological cell, we see layer after layer of building blocks. At a low level we have the 4 nucleotides that form the building blocks from which all chromosomes are constructed (Note that a physicist would add several levels of building blocks *below* this level, ranging from atoms down to quarks). One level up we have the 20 amino acids, coded by triplets of nucleotides, that form the building blocks for proteins. The proteins, in