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John H. Holland is professor of computer science and engineering and professor of psychology at the University of Michigan; he is also external professor and member of the board of trustees at the Santa Fe Institute.

He was made a MacArthur fellow in 1992 and is a fellow of the World Economic Forum. He is also a member of the International Academic Advisory Committee of the Chinese Academy of Sciences (AMSS).

Professor Holland has been interested in adaptation and complex adaptive systems (CAS) since the time he completed his PhD (1959). He formulated genetic algorithms, classifier systems, the Echo models, and gated urn models as tools for studying CAS dynamics. These tools, and the theoretical framework built with them, are presented in his books *Hidden Order* (1995), *Emergence* (1998), and *Signals and Boundaries* (2012).

Signals and Boundaries

Even a crude look at the whole earth ecosystem, and activities that depend upon it, requires a model with more than one level because:

(i) Most bio-carbon is recirculated through bacteria, while many interactions of interest involve multi-celled organisms.

> For example, 90% or more of the bio-carbon in this world is re-circulated by oceanic bacteria and in micro-biomes, such as the mammalian intestine, there are dozens of bacterial cells for each eukaryotic cell.

(ii) Interactions at the bacterial level are conditional and nonlinear.

> For instance, bacteria steer themselves along glucose gradients and aggregate to form spores under adverse conditions; there is also ubiquitous horizontal gene transfer amongst different bacterial species, so that new phenotypes arise continually.

Because of the conditional interactions, one cannot simply sum the activities of the component organisms to obtain the activity of the whole ecosystem – a new

level emerges with new laws (much as the Navier-Stokes laws of fluid flow emerge from the dynamics of individual molecules). A crude look that ignores these emergent levels would be similar to constructing a corporation budget that ignores 90% of the cash flow.

Different emergent levels in complex adaptive systems are determined by semi-permeable boundaries that "steer" resources and signals. These boundaries can be modeled by gated urns (which I will define) that, in turn, provide a way of using Markov processes to study the roles of signals and boundaries, at various levels, in the whole complex adaptive system.